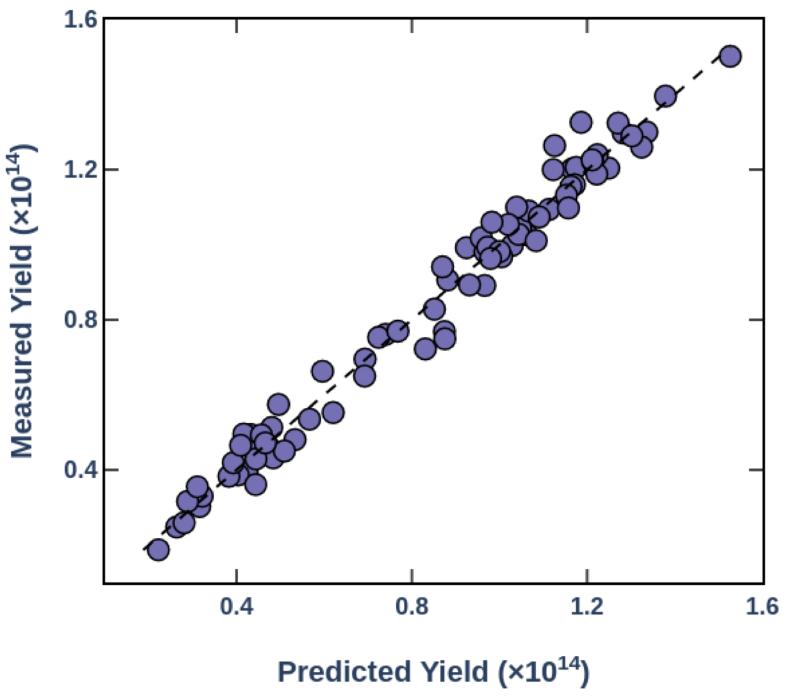
Toward Optimizing Cryogenic Inertial Confinement Fusion Implosions



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OMEGA cryogenic implosion performance has been optimized with respect to fuel composition and target age using the statistical mapping method

- **A cliff in target performance is found at a tritium fraction of 70%**
- **The optimum tritium concentration that maximizes the fusion yield is about 60% but this value may depend on the age of the DT fill**
- **The age of the DT fill is found to be correlated with loss of performance, with shorter fills leading to highest fusion yields**
- **We hypothesize that both the cliff in tritium fraction and the degradation from target age is due to tritium-induced radiation damage[1,2] or helium buildup**

1. Harding, D. R., and W. T. Shmayda. Fusion Science and Technology 63.2 (2013): 125-131.
2. Regan, S. P., et al. Nuclear Fusion 59.3 (2018): 032007.

Collaborators

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If experiments are systematically perturbed, it is possible to construct a predictive model from 1-D hydrocodes

Inputs not accounted for in simulations (e.g. target age)

Systematic nonuniformity seeds

Pulse shape and target specs

Experimental observables $\rightarrow \mathbf{O}^{\text{exp}} = \mathbf{F}_{\text{exp}}\left[\mathbf{I}_{1\text{D}}, \mathbf{I}_{\text{other}}, \mathbf{S}^{\text{sys}}_{3\text{D}}\right]$

1-D Simulated observables $\rightarrow \mathbf{O}^{\text{sim}}_{1\text{D}} = \mathbf{F}_{\text{sim}}\left[\mathbf{I}_{1\text{D}}\right]$ $\Rightarrow$ $\mathbf{I}_{1\text{D}} = \mathbf{F}^{-1}_{\text{sim}}\left[\mathbf{O}^{\text{sim}}_{1\text{D}}\right]$

Constant if systematic

$$\mathbf{O}^{\text{exp}} = \underbrace{\mathbf{F}_{\text{exp}}\left[\mathbf{F}^{-1}_{\text{sim}}\left(\mathbf{O}^{\text{sim}}_{1\text{D}}\right), \mathbf{I}_{\text{other}},\right.}\left.\mathbf{S}^{\text{sys}}_{3\text{D}}\right]$$

$$\boxed{\mathbf{O}^{\text{exp}} \approx \mathbf{F}_{\text{map}}\left[\mathbf{O}^{\text{sim}}_{1\text{D}}, \mathbf{I}_{\text{other}}\right]}$$ $\Leftarrow$ **Predict experiment from 1D simulation**

Statistical mapping enables optimization with respect to less dominant effects such as tritium radiation damage and target age not included in 1-D codes

- Fuel composition (tritium fraction) and target age are included in the statistical model to optimize implosion performance
- Both of these variables can affect the extent of radiation damage to targets due to tritium decay and helium buildup
- Higher tritium content improves ablation pressure but increases β radiation damage. An optimum tritium fraction must be found
- The statistical mapping model accounts for all the major contributors to performance allowing us to examine these relatively smaller effects that would otherwise be masked by shot-to-shot variability

Prediction ➡

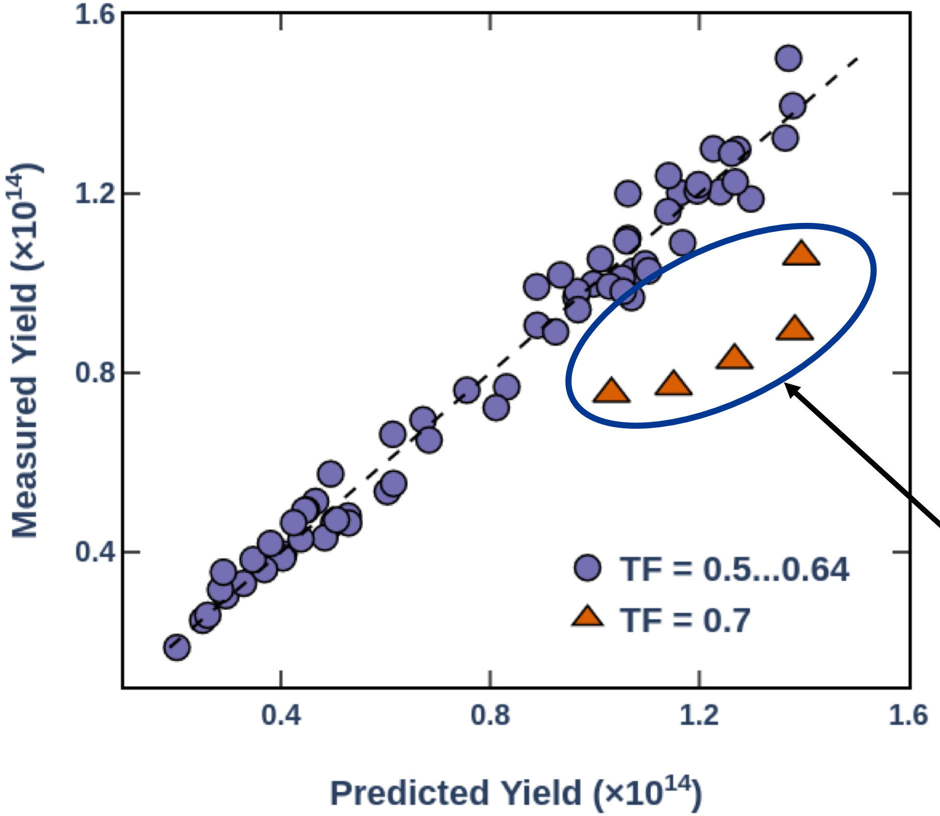
$$O^{exp} = F_{map}\left[O_{1D}^{sim},\, I_{other}\right] \xrightarrow{\text{e.g.}} \underbrace{\left(V_{imp}^{sim}\right)^{4}\left(\rho R^{sim}\right)^{0.3}}_{\text{Implosion dynamics}} \cdots \underbrace{\left(\text{Fill Age}\right)^{-0.17}}_{\text{Other inputs}}$$

Account for variability in implosion dynamics including systematic 3D effects[1]

Effects from other inputs not captured by hydro codes

1. V. Gopalaswamy, next talk

Increasing the tritium fraction to 70% led to a “cliff” in performance not predicted by the statistical model



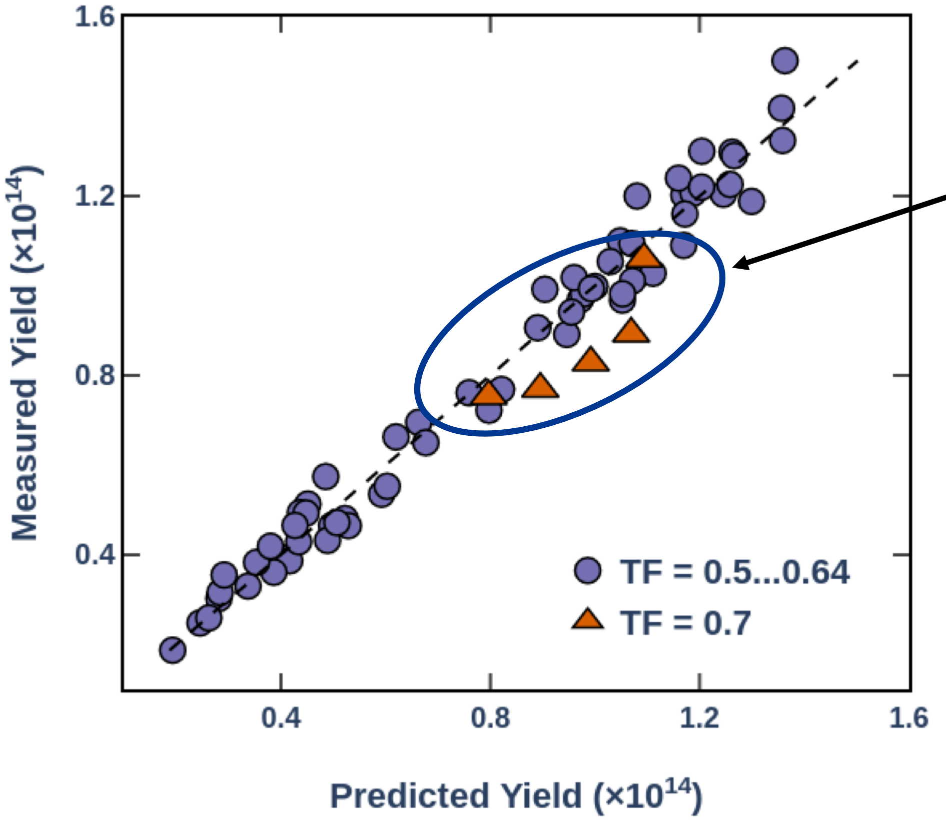
- The database used to train the statistical model included tritium fractions from 50% to 64%

Shots with 70% tritium were overpredicted

$\propto (\mathbf{TF})^{0.15}$

Data up to July 2019 shows a weak dependence on tritium fraction (TF)

Adding a tritium fraction dependence on (1 – TF) improves the pre-shot prediction of the "cliff"

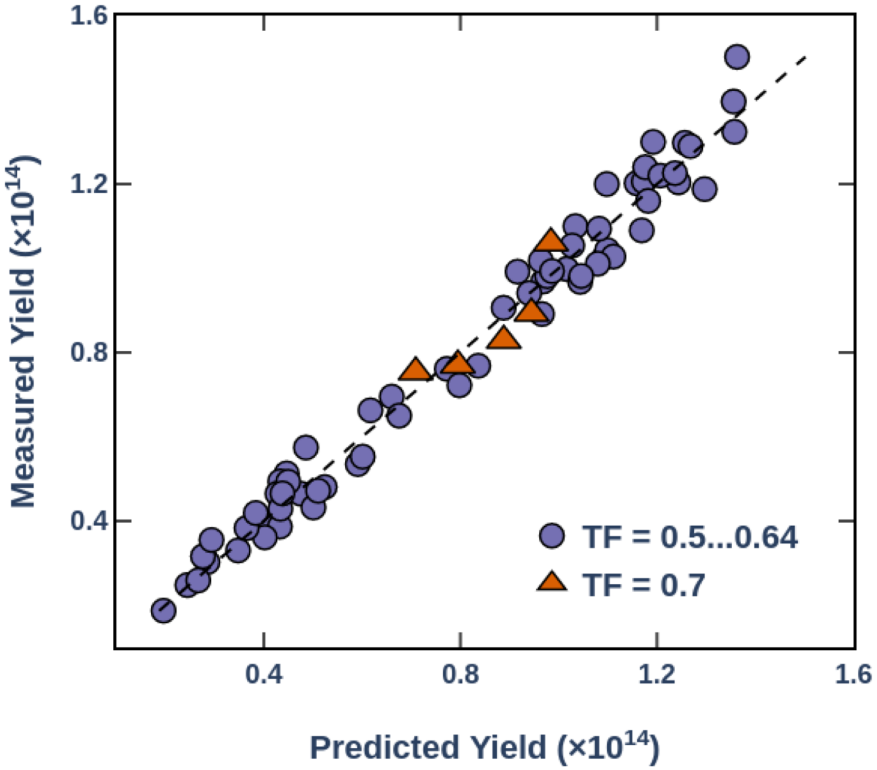


$$\propto (\mathbf{TF})^{3.76}(1-\mathbf{TF})^{2.76}$$

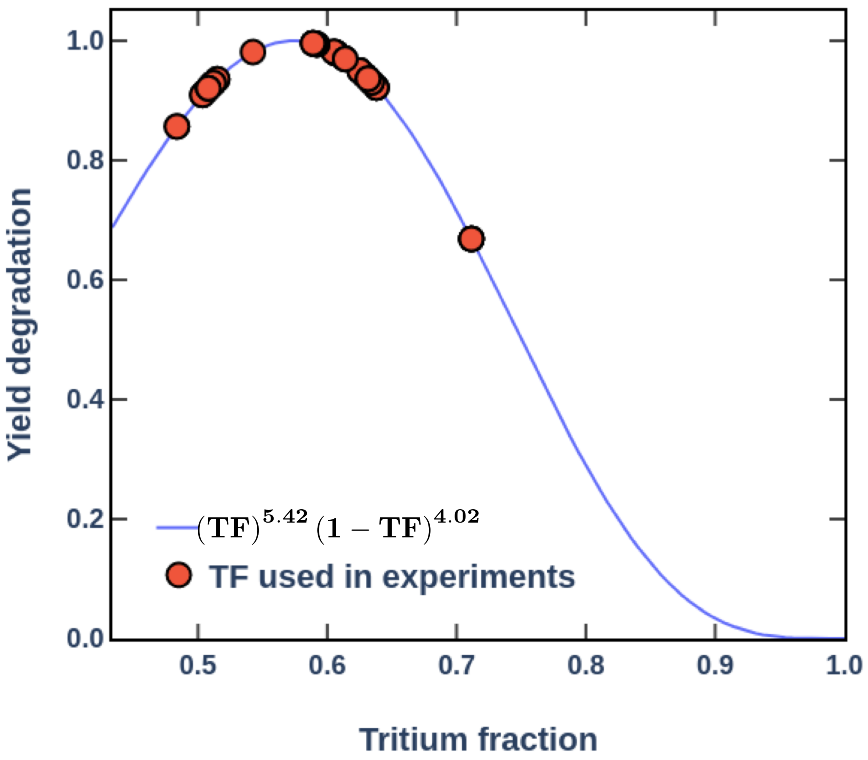
- **The updated model including (1-TF) dependence better predicts the 70% tritium shots**
- **Including (1 – TF) shows a strong dependence with a sharp drop in performance at high tritium fractions [but low confidence level for database with TF=0.5-0.64]**

The optimum tritium concentration that maximizes the fusion yield is about 60%

Includes all TF = 0.5-0.7



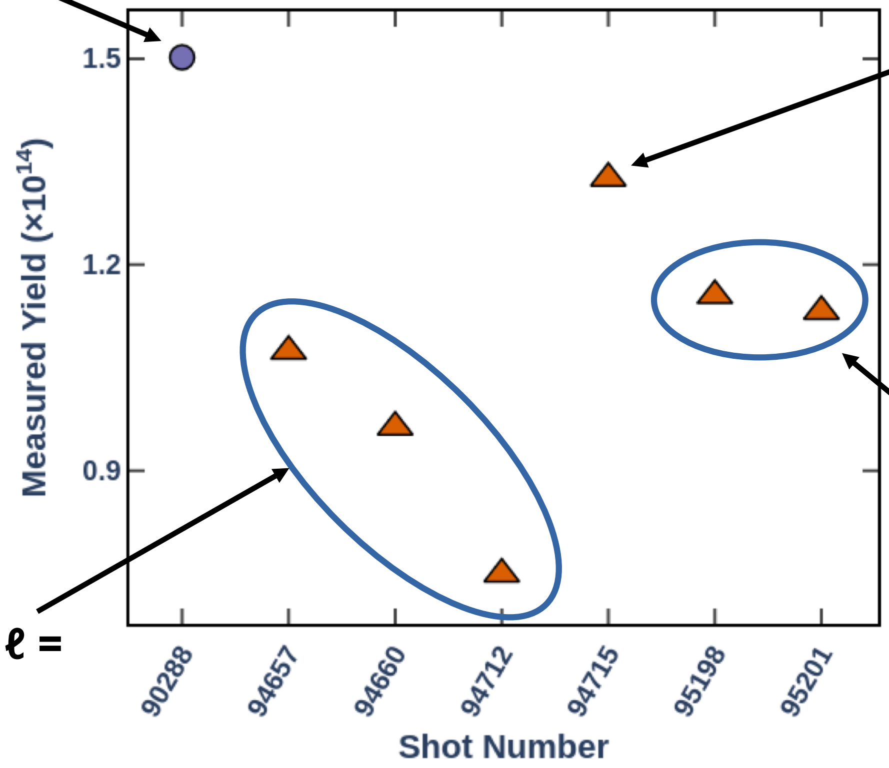
$$\propto (\mathbf{TF})^{\mathbf{5.42}}\,(\mathbf{1}-\mathbf{TF})^{\mathbf{4.02}}$$



Several recent attempts failed to repeat the fusion yield of best performing implosion of 2018 (90288)

Best performer 90288

Target intentionally offset to compensate for low mode in laser (shot 94715)



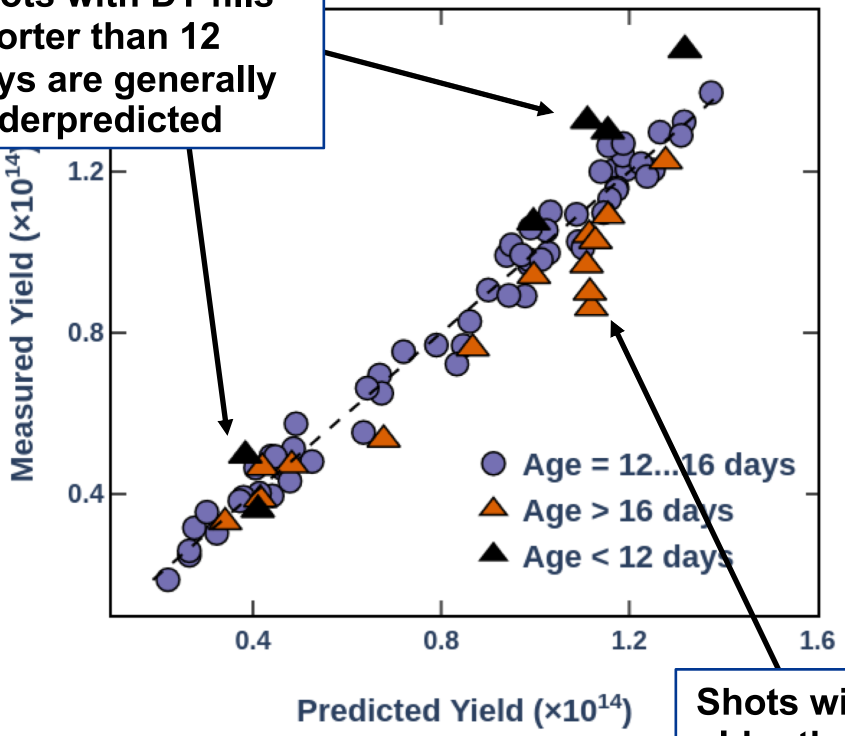
Shots with improved pointing still failed to repeat the yield of shot 90288

Yield degraded by large ℓ = 1 mode due to laser mispointing

The effect of DT fill age was investigated and found to considerably improve the post-shot predictions

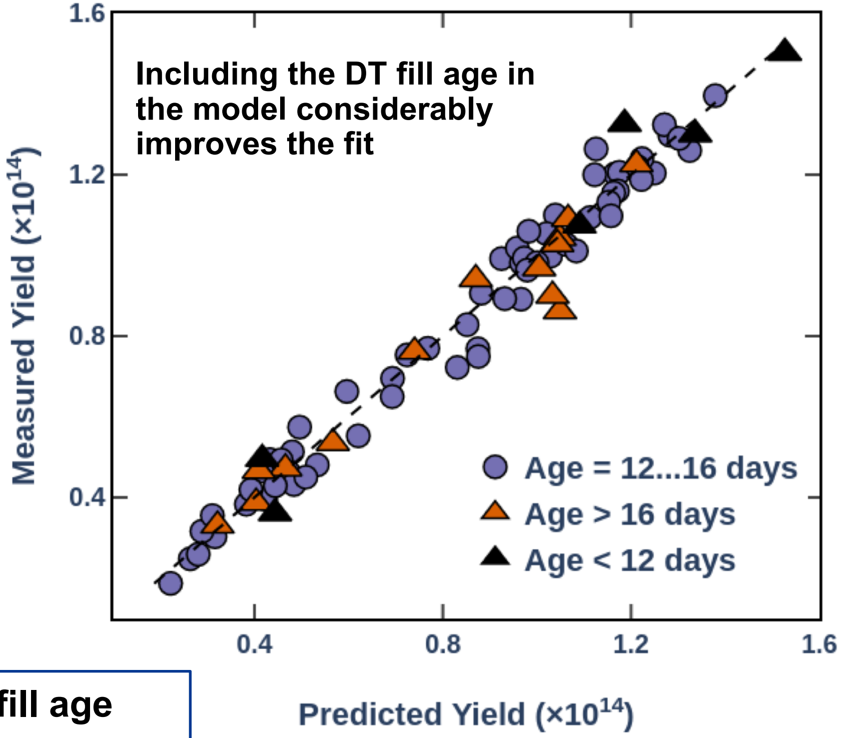
Mapping from data with fill age 12-16 days

Shots with DT fills shorter than 12 days are generally underpredicted



Shots with DT fill age older than 16 days are generally overpredicted

Mapping including all fill ages

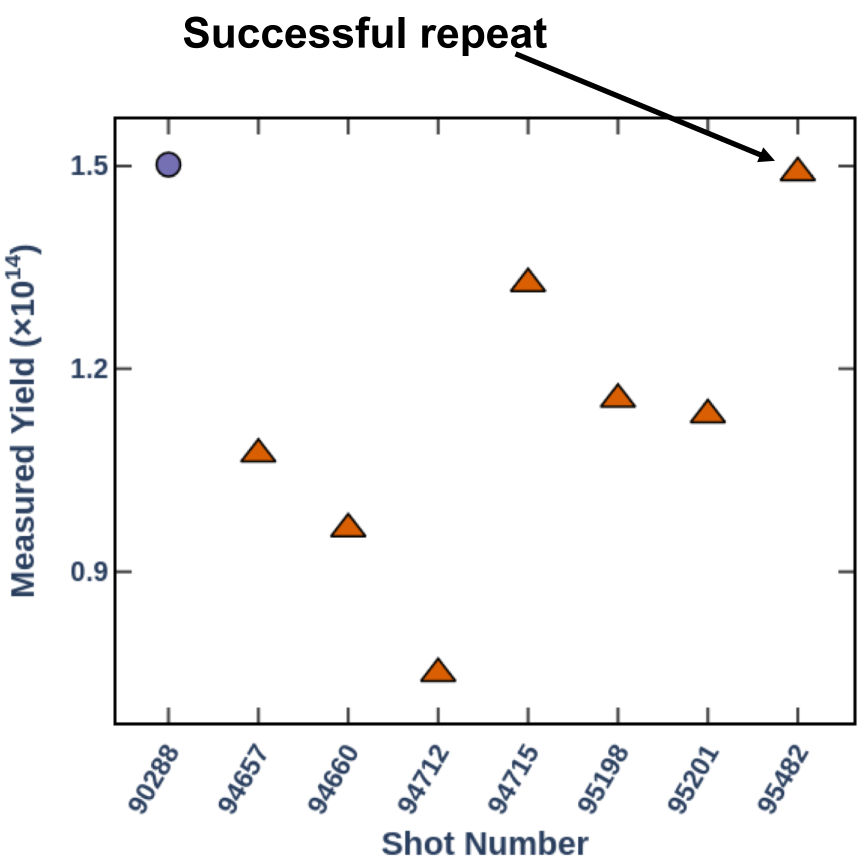


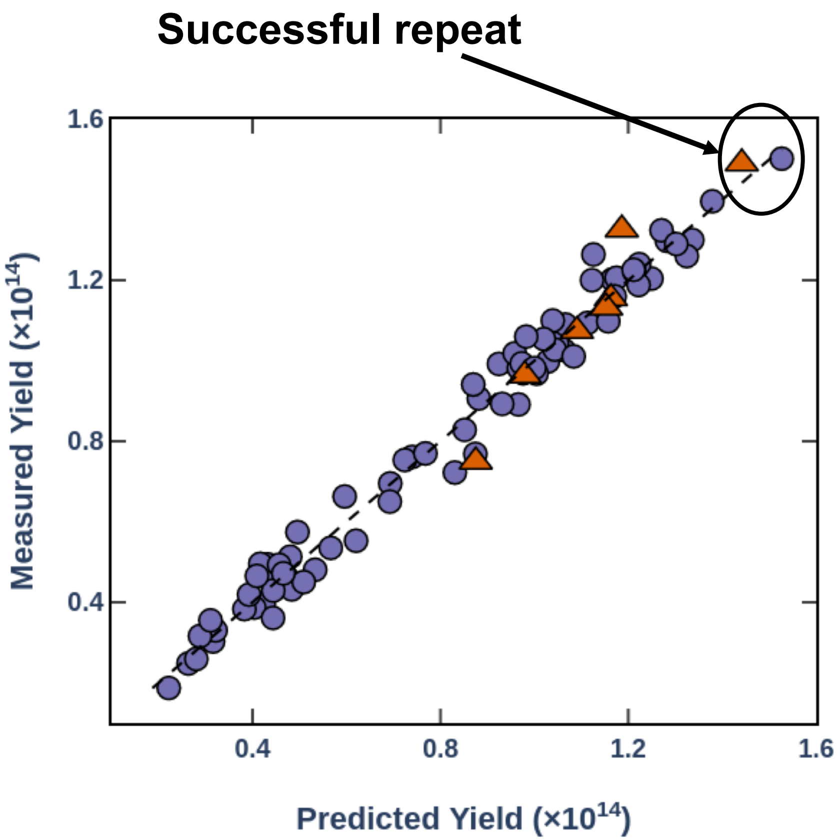
$$\propto (\textbf{Fill Age})^{-0.17}$$

Younger DT fill age leads to higher performance

Fill age = Time in days between fill start and shot time

The best-performing implosion was successfully repeated on a target with an 8-day-old DT fill





Summary/Conclusions

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