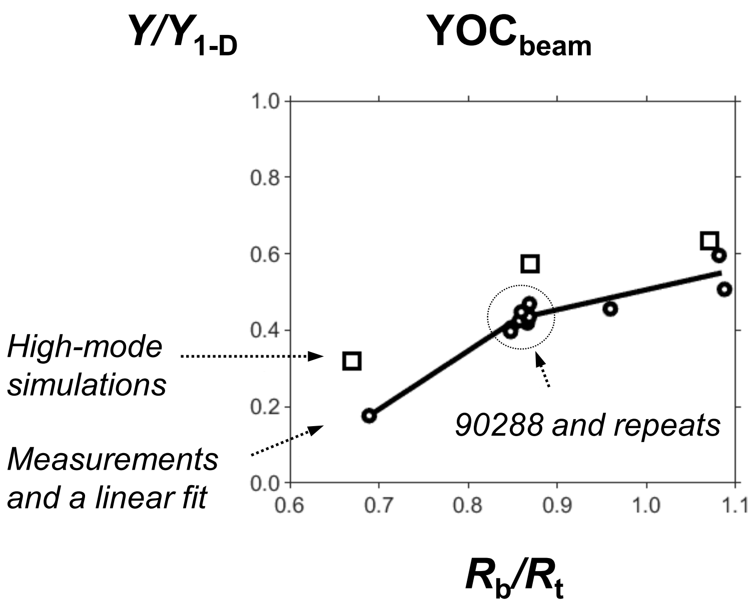
Using parameter scans to quantify, optimize, and extrapolate performance metrics for cryogenic implosions at OMEGA

$$Y_{exp} \sim Y_{1\text{-}D}\ YOC_{beam}(R_b/R_t)\ YOC_{hydro}(IFAR)\ YOC_{residual}(Scale)$$

Experimental yield Y_{exp}
Simulated yield $Y_{1\text{-}D}$
Yield over calculated YOC
Beam radius R_b
Target radius R_t
In-flight-aspect-ratio IFAR
Scale = R_t / 479 um



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Multiple cryo campaigns have identified and refined the features in data that need to be captured by statistical models[1-2] and simulations

$Y_{exp} \sim Y_{1\text{-}D}\,\mathrm{YOC}_{beam}(R_b/R_t)\,\mathrm{YOC}_{hydro}(IFAR)\,\mathrm{YOC}_{residual}(Scale)$

YOC_{beam} : Fusion yields rise quickly at $R_b/R_t \sim 0.7$ to 0.8, then slow at $R_b/R_t \sim 1$

YOC_{hydro} : *Y* and *ρR* decrease relative to expectations at high *IFAR*, then appear to asymptote

$\mathrm{YOC}_{residual}$: Target size is a factor in performance at OMEGA, and could play a role in extrapolation

[1] V. Gopalaswamy et al., Nature 565, 581-586 (2019)
[2] A. Lees et al., Phys. Rev. Lett. 127, 105001 (2021)

Collaborators

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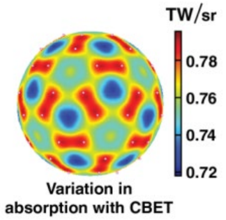
University of Rochester Laboratory for Laser Energetics

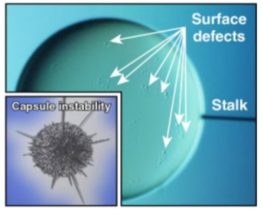
Statistical methods are used to study mechanisms in physics, evaluate tradeoffs in target design, and correct for sources of variance[1-2]

$$Y_{exp} \sim Y_{1\text{-}D}\, \mathrm{YOC}_{beam}(R_b/R_t)\, \mathrm{YOC}_{hydro}(IFAR)\, \mathrm{YOC}_{residual}(Scale)$$

YOC_{beam}



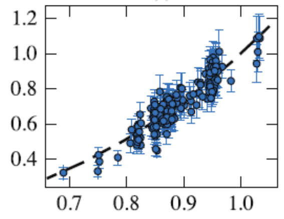
YOC_{hydro}



$\mathrm{YOC}_{residual}$

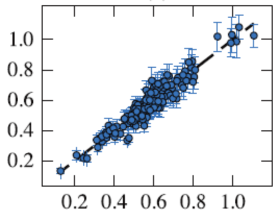
Target scale? Other weak sensitivities?

$Y/Y_{1\text{-}D}$



Func(R_b/R_t)

$Y/Y_{1\text{-}D}$

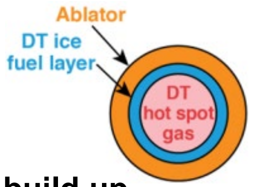


Func($IFAR$)

Power law fits to data

Two additional terms are very well-established

YOC_{fuel}



He build up
β-decay damage

$\mathrm{YOC}_{mode\ 1}$

Laser pointing

Analyses in these slides include adjustments for fuel age and mode 1, which are typically 10-20% in yield

[1] V. Gopalaswamy et al., Nature 565, 581-586 (2019)
[2] A. Lees et al., Phys. Rev. Lett. 127, 105001 (2021)

Predictive formula are impacted by several sources of uncertainty

$$Y_{exp} \sim Y_{1\text{-}D}\, YOC_{beam}(R_b/R_t)\, YOC_{hydro}(IFAR)\, YOC_{residual}(Scale)$$

Assume a power law expansion:

$$Y_{exp} \sim Y_{1\text{-}D}\, (R_b/R_t)^{N1}\, (IFAR)^{N2}\, (Scale)^{N3}$$

Solve for 'minor term' like Scale:

$$N3 \log(Scale) + \log(C) \sim \log(Y_{exp}/Y_{1\text{-}D})$$

$+ \Delta Y_{exp}$ — *Measurement errors*

$+ \Delta Y_{1\text{-}D}$ — *Details in simulation, e.g. pulse-shaping*

May be unknown, and exceed experimental errors

$+ \Delta(N1 \log(R_b/R_t))$ — *Other terms, unintended correlations*

$+ \Delta(N2 \log(IFAR))$ — *Again, can be >> experimental errors*

In the data that follows, most of these issues are reduced (or avoided) by design

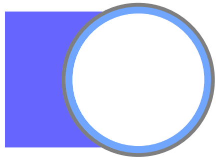
Single-variable studies were performed over a wide parameter space, all of which are related to experiment 90288, which is a common standard candle

1. $YOC_{beam}(R_b/R_t)$

IFAR and Scale ~ Constant

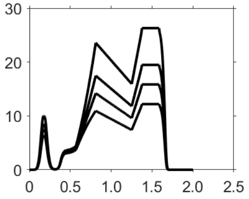
Permutations in the available phase plates and target radius

R_t 384 to 480 um



R_b 332 to 415 um

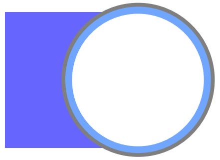
Laser pulses modified to match on pressure vs time, adiabat, trajectory, etc.



2. $YOC_{hydro}(IFAR)$

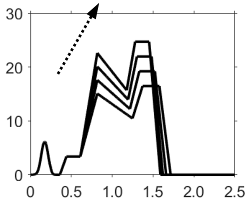
R_b/R_t and Scale ~ Constant

R_t 384 um



R_b 332 um

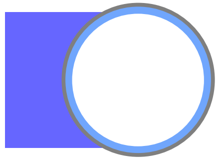
Increased laser intensity



3. $YOC_{residual}(Scale)$

R_b/R_t and IFAR ~ Constant

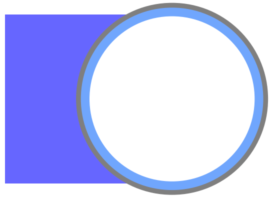
R_t 384 um



Euler-scaled version of 90288

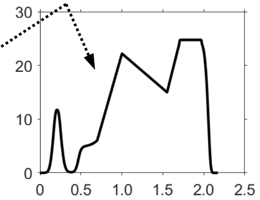
R_b 332 um

R_t 480 um



R_b 415 um

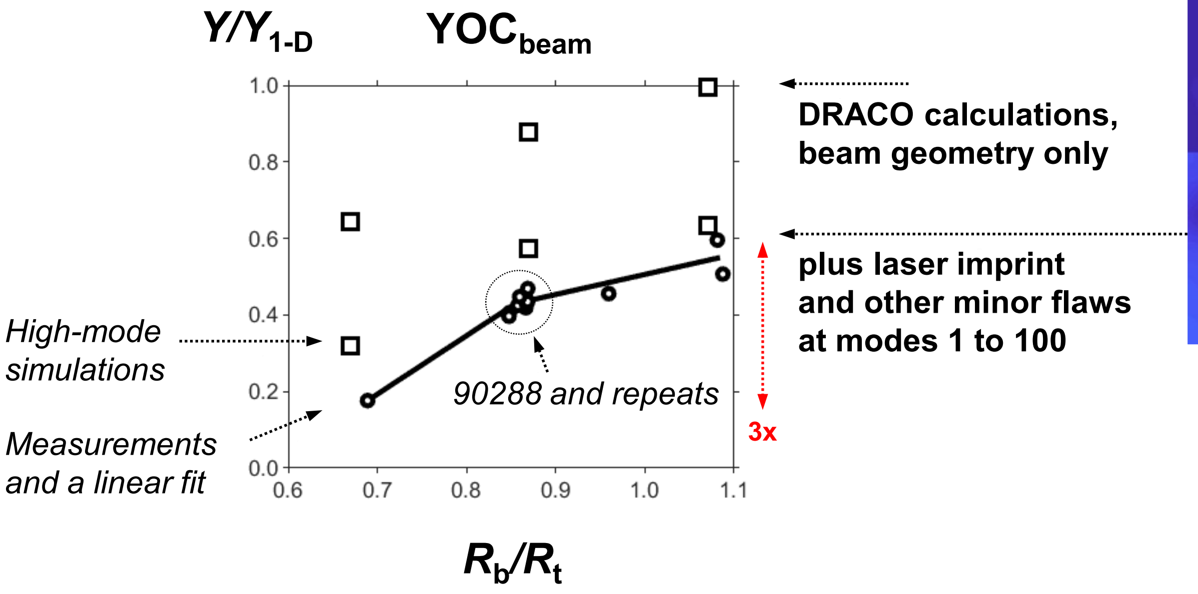
90288



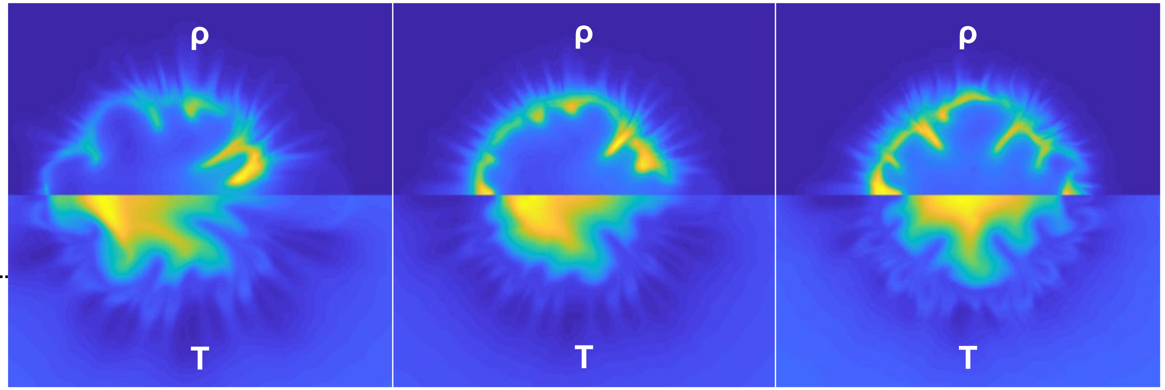
Results can be used to motivate new predictions, but for now, we'll just take a tour of data

Neutron yield is a strong function of beam-to-target radius, R_b/R_t, and high-mode imperfections in the laser and target

All yields are normalized by 1-D calculations in LILAC[1]



Cold shell and hot spot at stagnation



$R_b/R_t = 0.67$ | $R_b/R_t = 0.87$ | $R_b/R_t = 1.07$

6 | 10 | 14

Approx beam overlaps

Yield is tightly correlated to the seeding of high-mode imperfections in the shell
Additional data could improve stat significance and enable comparisons on ρR

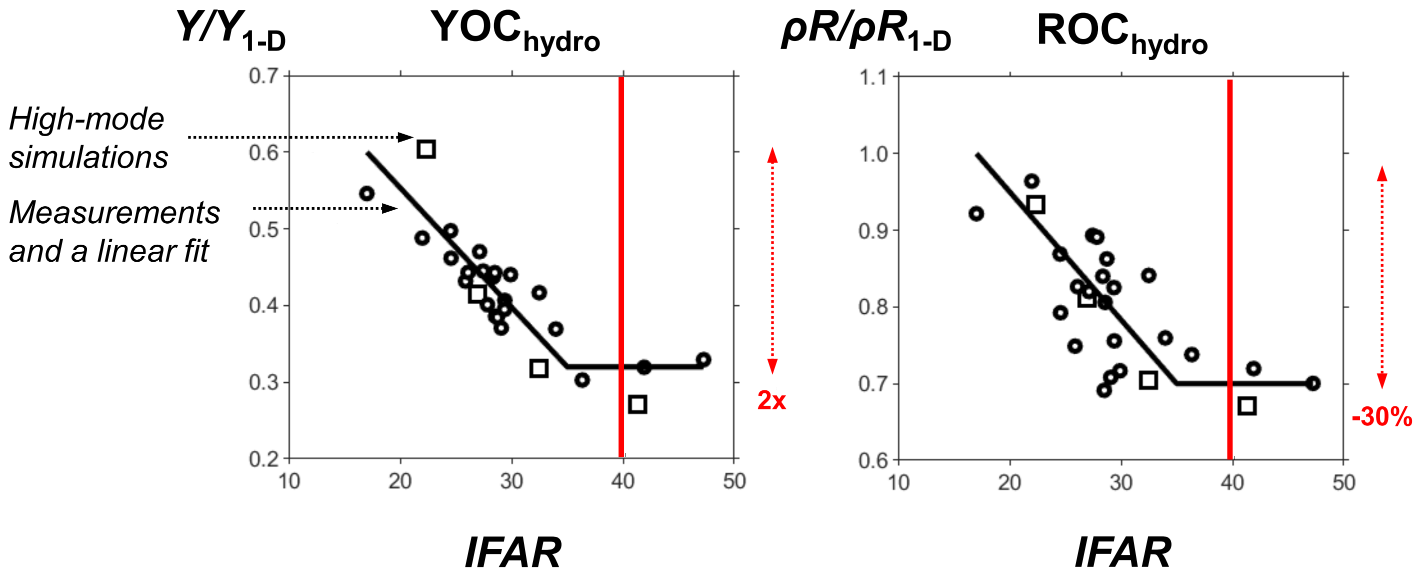
Simulations in DRACO[2] may not include or fully resolve all degradations, but match trends in data

[1] J. Delettrez et al., Phys. Rev. A 36, 3926 (1987)
[2] P. Radha et al., Phys. Plasmas 12, 032702 (2005)

Y and *ρR* decrease with *IFAR* and measures of stability, then level off at or near a critical in-flight-aspect-ratio[1]

Yield and ρR are normalized by 1-D calculations in LILAC

$IFAR_{crit}$ ~ 20 (Adiabat/3)$^{1.1}$ ~ 40



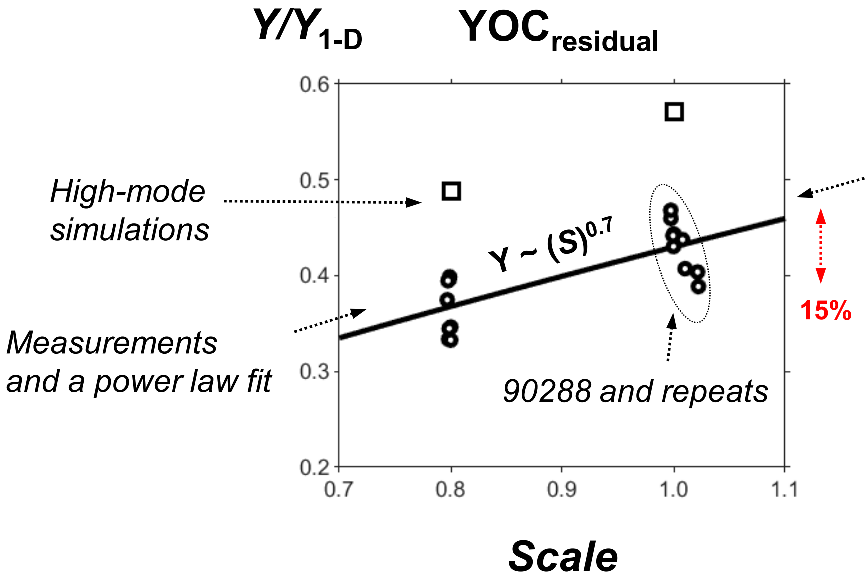
Is it plausible for instabilities to grow until they relax 1-D gradients, and saturate or limit further degradations?

2-D simulations may have difficulty reproducing the same asymptote – 3-D may be required

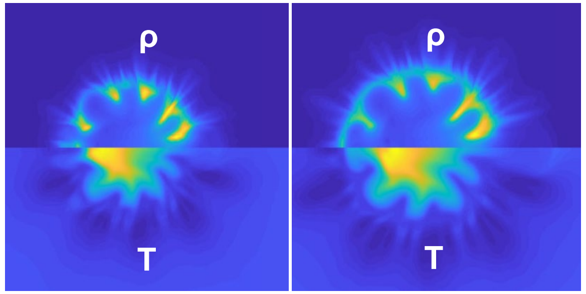
[1] V. Goncharov et al., Phys. Plasmas 21, 056315 (2014)

Results vs *Scale* indicate a weak dependence on target size – and make sense, if implosion quality is a function of flaws and hydro

All yields are normalized by 1-D calculations in LILAC[1]



Can only be inferred by eliminating uncertainties associated with R_b/R_t and IFAR, and doing a large number of experiments at widely separated scales.



***Scale* = 0.8** ***Scale* = 1.0**

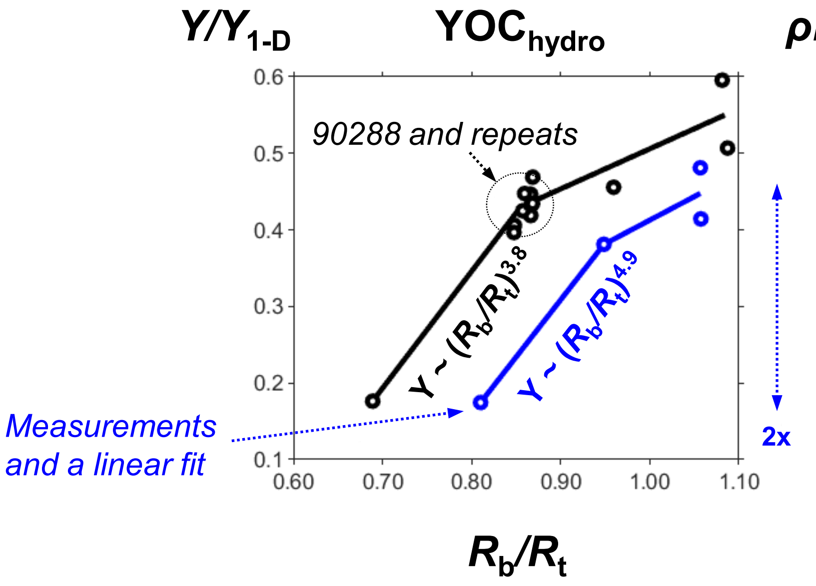
Calculations in DRACO including nominal levels of imprint, capsule roughness, errors in laser pointing, and a target offset (5 um). Both are similar, but not self-similar (vs scale). Real experiments are also subject to dust and debris, and the target stalk.

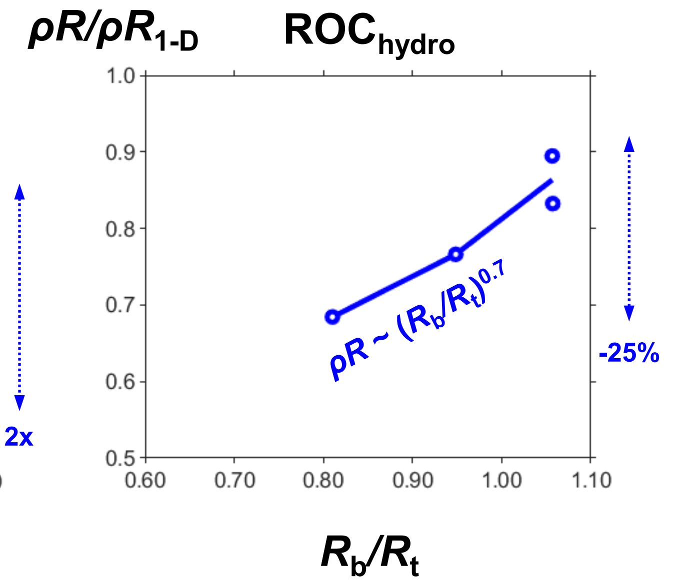
Impacts are small at OMEGA, but could be significant for large extrapolations

Current and upcoming experiments will probe the same sensitivities at lower adiabat (below: new data on R_b/R_t)

Yield and ρR are normalized by 1-D calculations in LILAC

Implosions with pulse shape 90288 and a DT adiabat ~ 5
Implosions with pulse shape 98541 and a DT adiabat ~ 3





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Yield over calculated YOC
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Additional data will improve statistical significance, and help guide future models

Experiments designed for next year will revisit high *IFAR*, again, but in a regime that could achieve high yields and areal densities

1. Start with stat formula for 90288-like experiments in Y and ρR

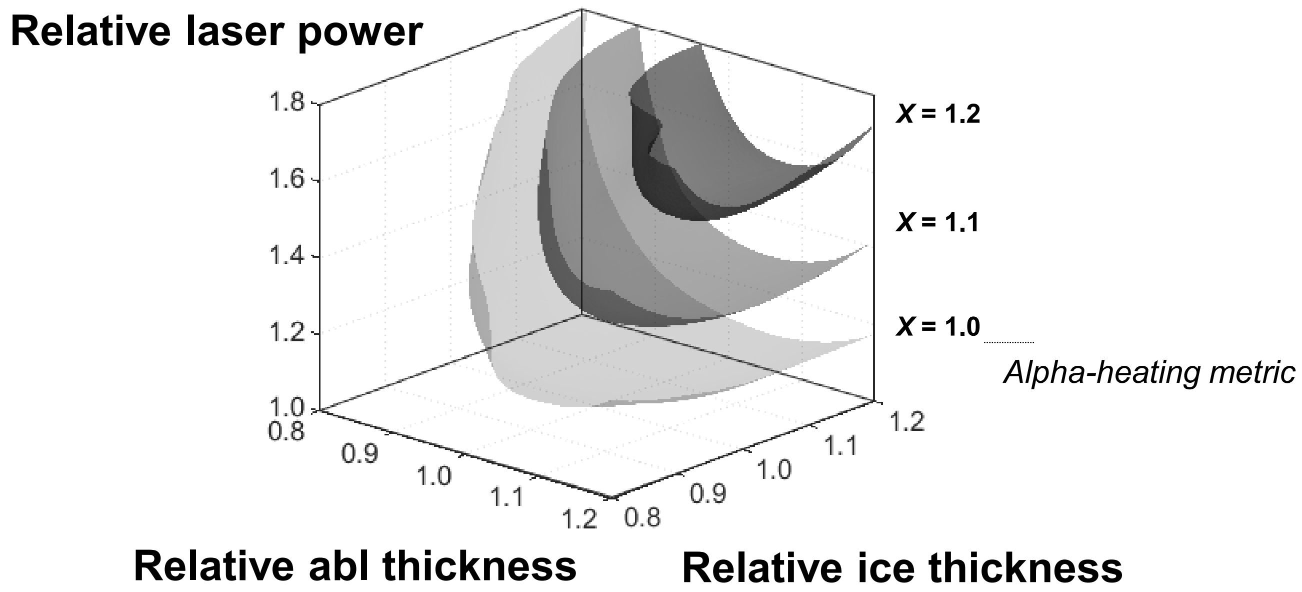
$YOC_{beam}(R_b/R_t)$ $ROC_{beam}(R_b/R_t)$
$YOC_{hydro}(IFAR)$ $ROC_{hydro}(IFAR)$
$YOC_{scale}(Scale)$ $ROC_{scale}(Scale)$

2. Build a database of 1-D calculations and re-tune

R_b/R_t = 0.47:0.05:1.07
Relative abl thickness = 0.5:0.05:1.5
Relative ice thickness = 0.5:0.05:1.5
Relative laser power = 1.0:0.05:2.0
Relative size = 0.8:0.1:4.0

3. Combine to predict plausible 90288-like experiments

Projection at R_b/R_t = 0.9 and Scale = 0.9



Same tools suggest the energy to ignite could be smaller than currently appreciated, ~ 2x

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