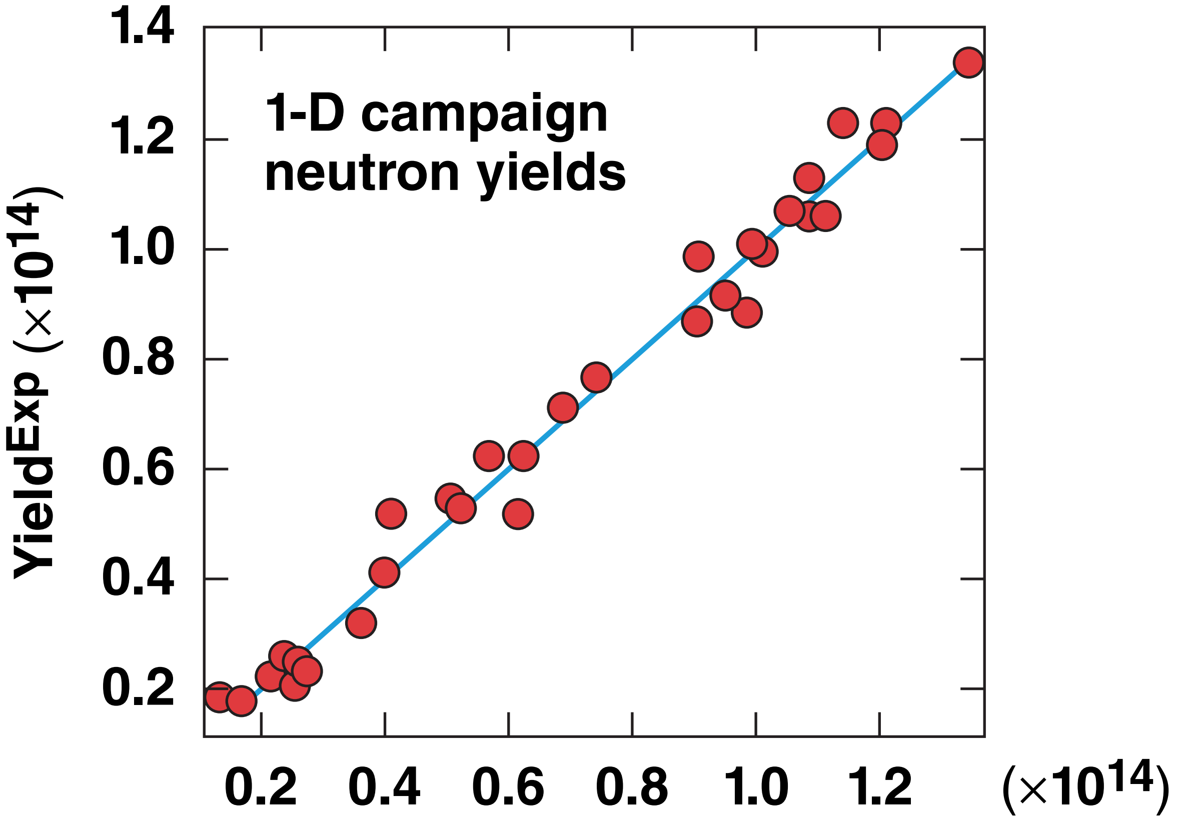
The 1-D Cryogenic Implosion Campaign on OMEGA



$$4.5\times10^{13}\left(\frac{V_{imp}^{LILAC}}{400}\right)^{4}\left(\frac{M_{stag}^{LILAC}}{0.01}\right)^{0.8}\left(\frac{T_{min}}{T_{max}}\right)$$

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Division of Plasma Physics
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Summary

High-adiabat ($\alpha \approx 6$ to 7) implosions achieved the highest fusion yields of 1.4×10^{14} on OMEGA with high predictability using a statistical mapping model

UR LLE

- The ongoing 1-D campaign is building an experimental database of high-adiabat, low-convergence implosions (CR* ~ 12 to 14)
- The highest fusion yield of 1.4×10^{14} (tripled in the past year) is achieved by increasing the target outer diameter and reducing the DT ice thickness
- Based on these recent results, a roadmap is being developed to find the optimum target and laser pulse

*CR: convergence ratio

Collaborators

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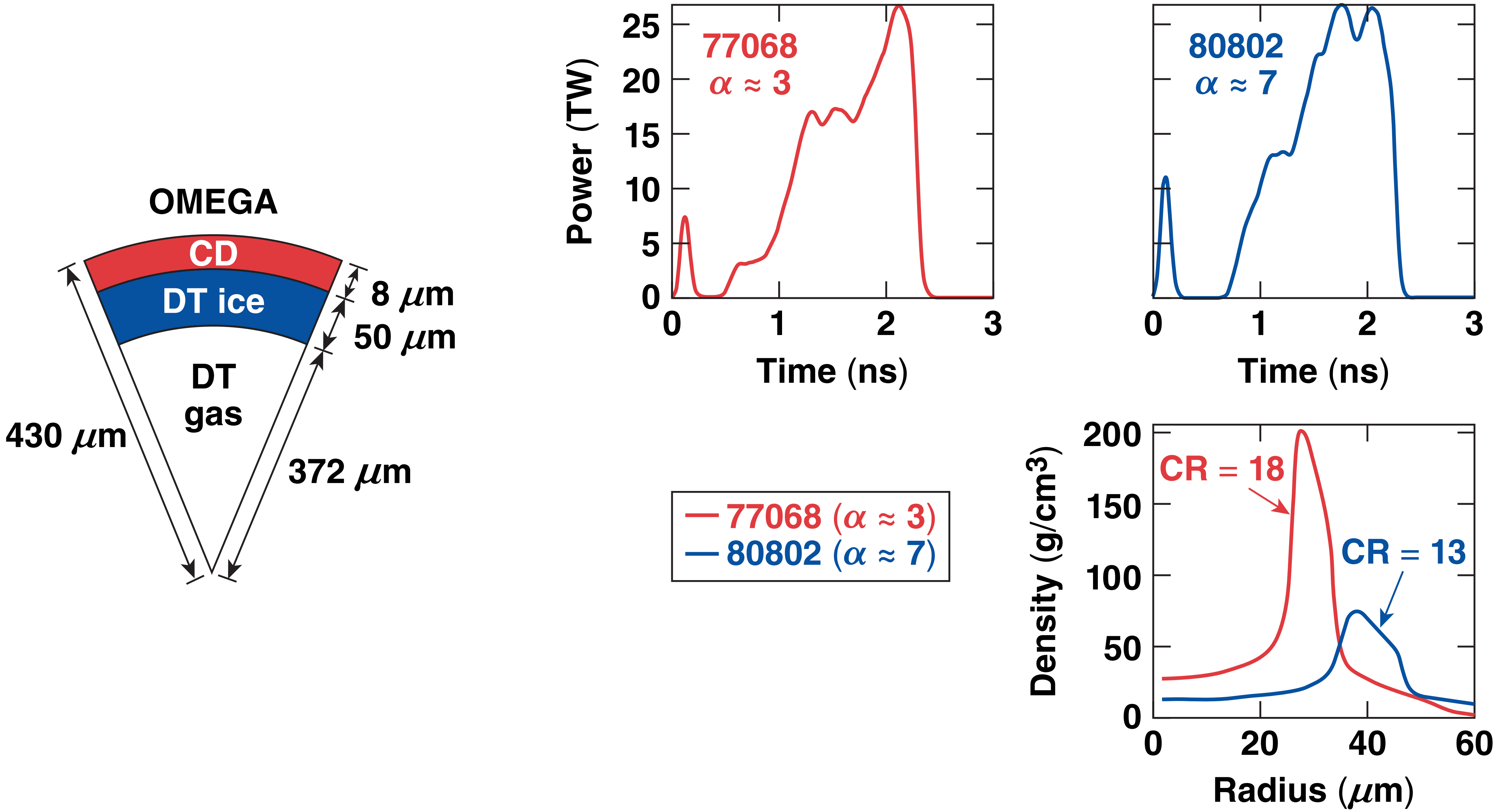
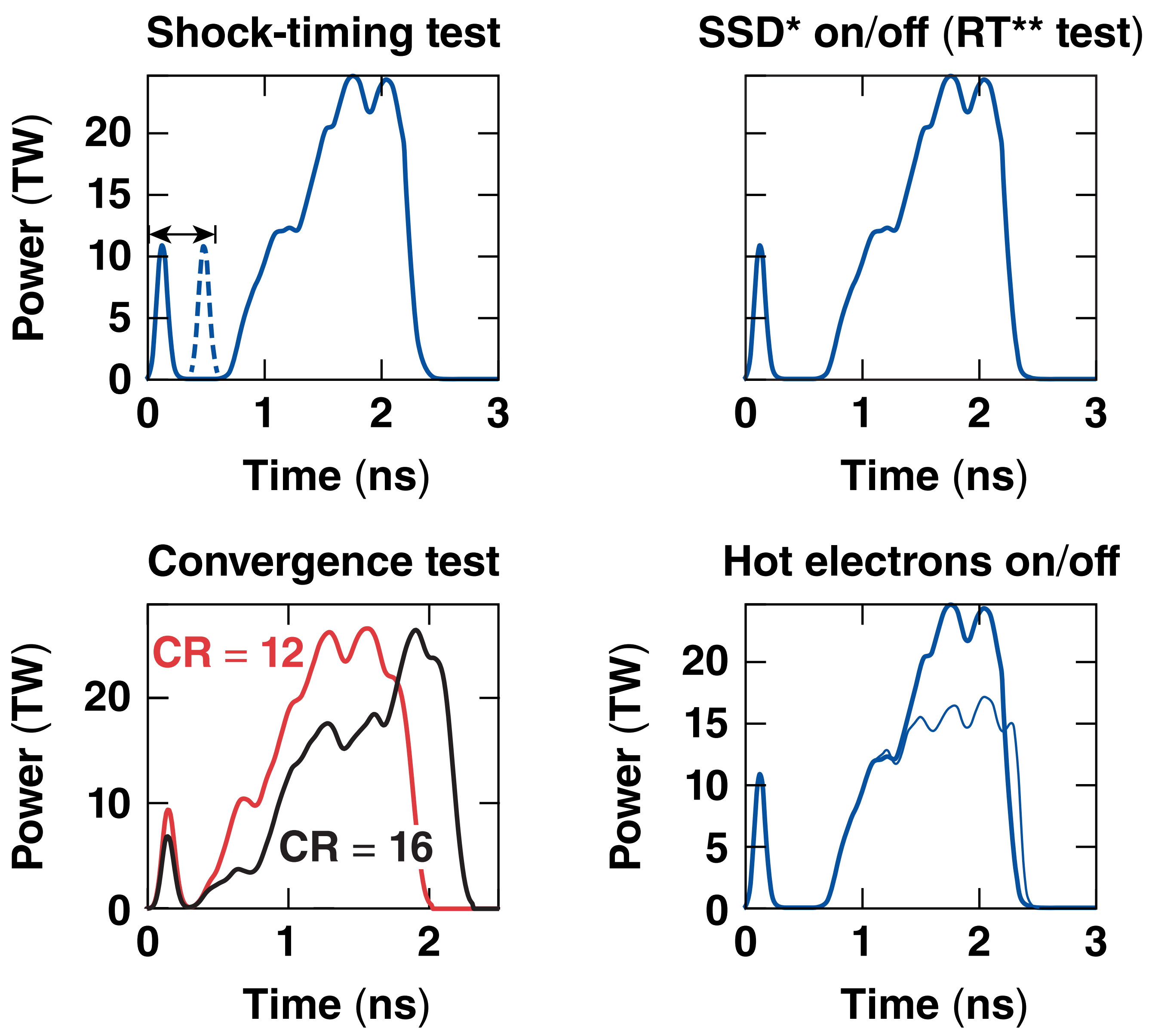
The 1-D Campaign Implosions

The 1-D Campaign developed a database of more-predictable, lower-convergence, high-adiabat implosions



TC13096b

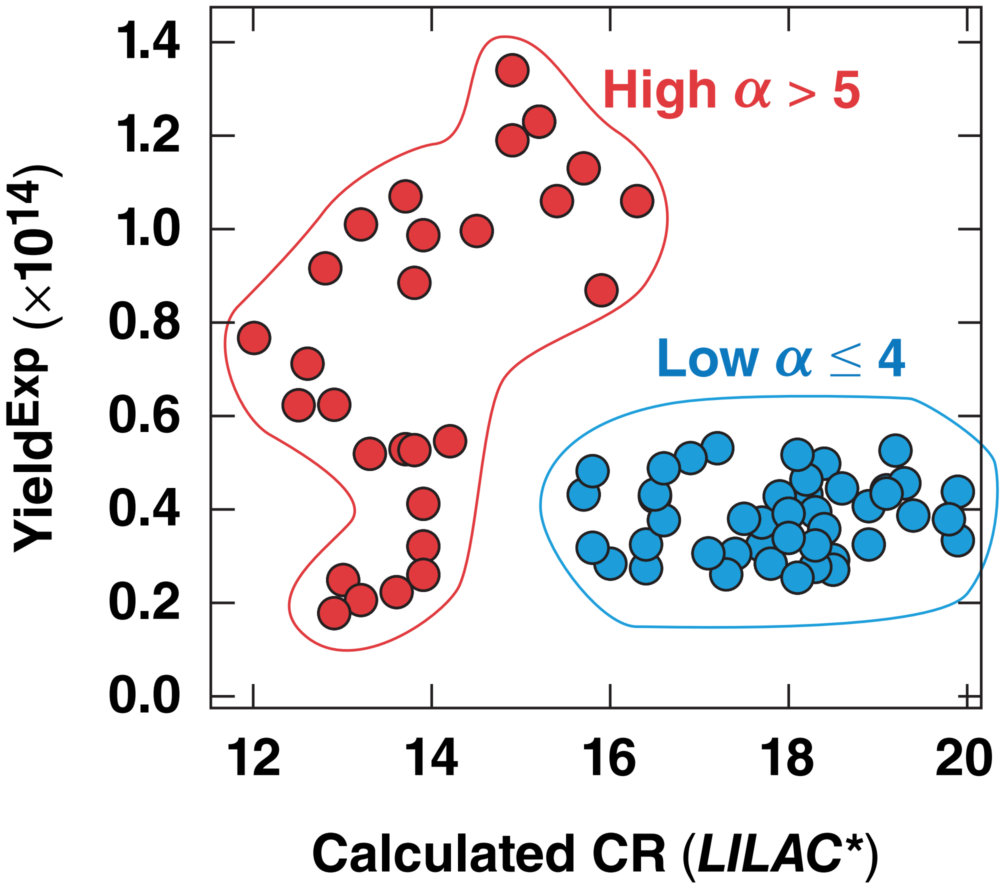
Systematic hydro-stability, convergence, shock-timing, and preheat tests are conducted to assess degradation mechanisms and proximity to stability cliffs

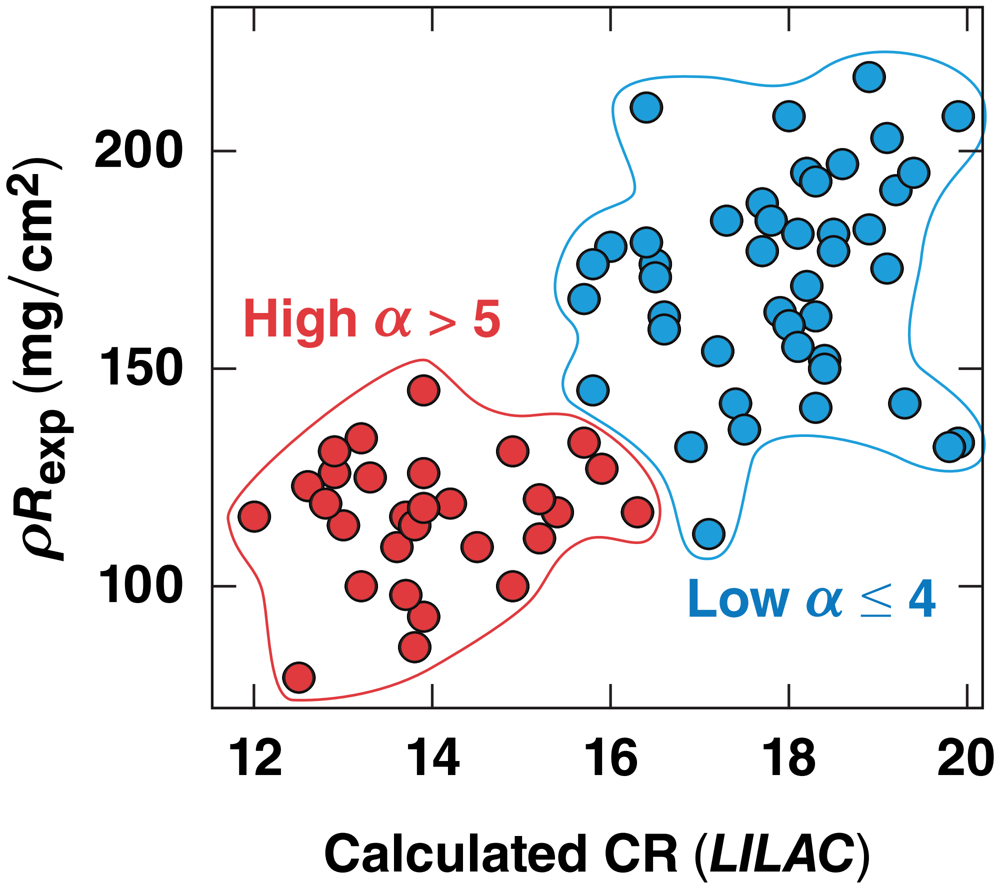


*SSD: smoothing by spectral dispersion
**RT: Rayleigh–Taylor

TC13095b

To date, high-adiabat, low-convergence implosions achieved the highest fusion yields on OMEGA with areal densities up to ~65% of the highest compression shots

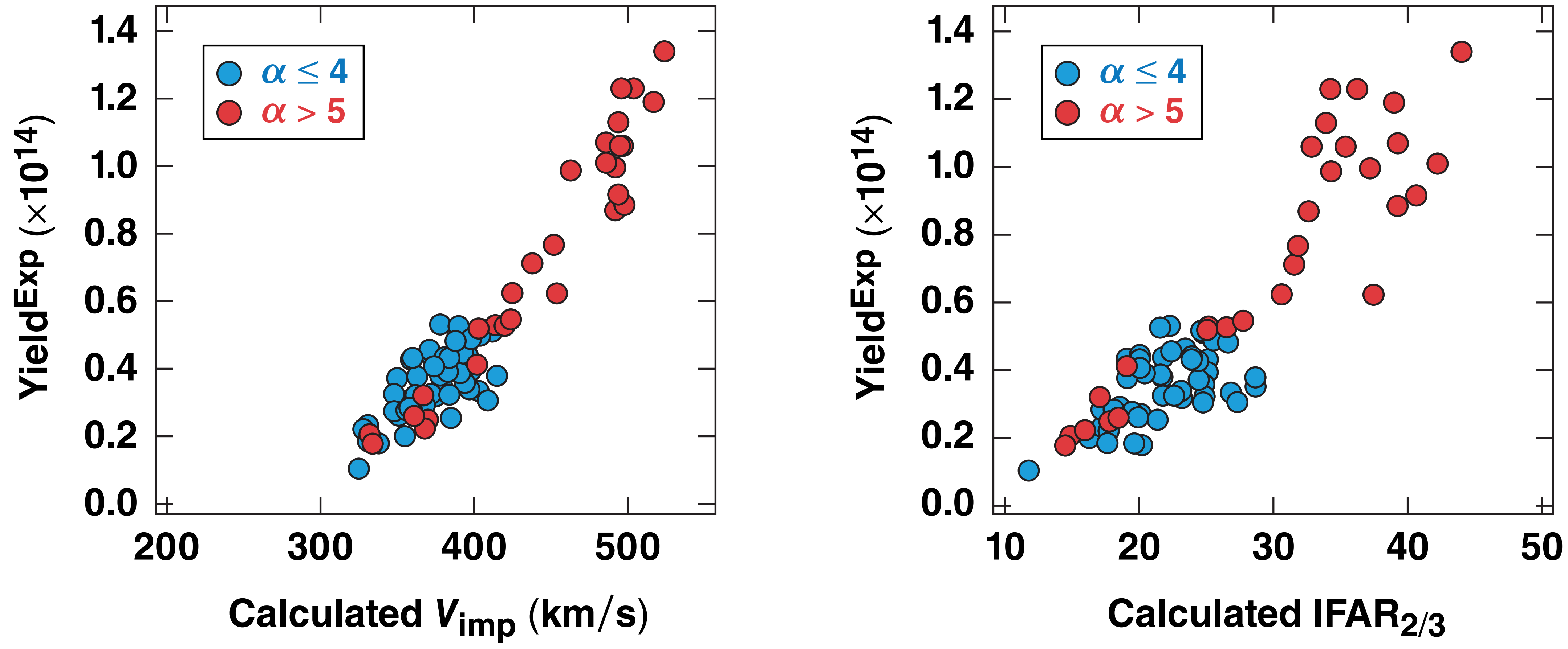




TC13677b

*LILAC is the LLE 1-D hydrodynamics code

As expected, the main dependence of the yield is on the implosion velocity



OMEGA implosions are testing the IFAR* limits.

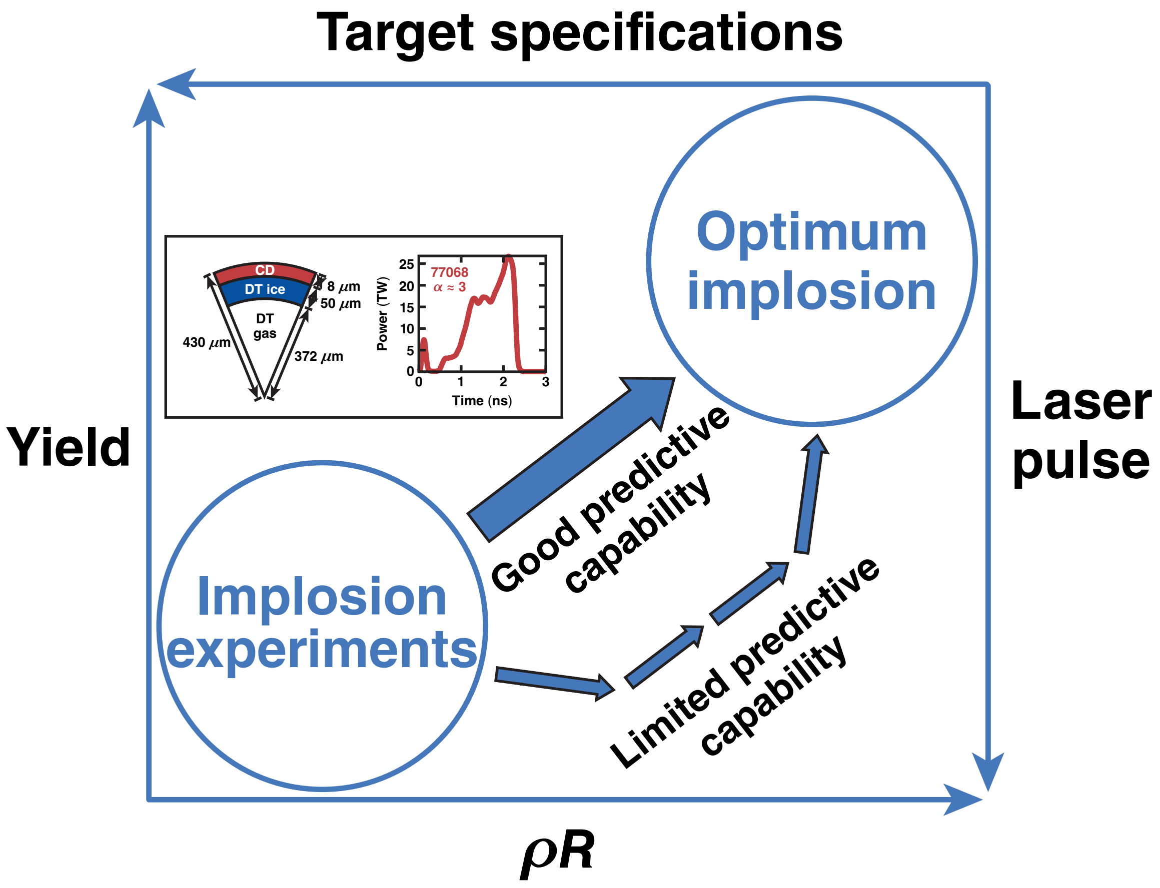
*IFAR: in-flight aspect ratio

The Statistical Mapping Model as a Predictive Tool

V. Gopalaswamy and R. Betti, CO8.00010, this conference.

A reliable predictive capability is required to find the optimum implosion

- Conventional predictive capability is based on using simulations to design future experiments
- Despite advances in simulations, codes are still not predictive enough to enable quick progress in improving implosion performance



Implosion performance figure of merit

- Lawson parameter χ*
- Experimental ignition threshold factor (ITFx)**

ITFx and χ scale with

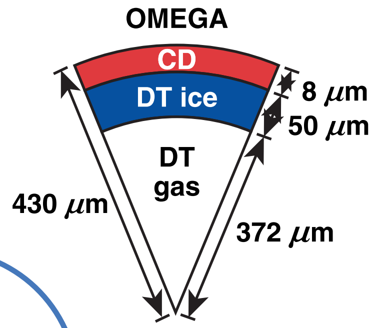
$$\rho R^2 \times \frac{\text{yield}}{\text{mass (DT)}}$$

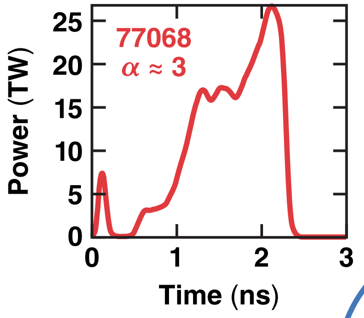
*R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).
**B. K. Spears *et al.*, Phys. Plasmas 19, 056316 (2012).

TC13679a

By assuming that the 1-D codes do not accurately reproduce the 1-D implosion dynamics, we look for statistical correlations between experimental and simulated data

Laser pulse and target specifications are inputs to both the code and the experiment





Assuming 1-D implosions

1-D physics models (*LILAC*)

Implosion experiment: real physics

Code output:

Yield^{LILAC}, V_{imp}^{LILAC}, ρR^{LILAC}, T_i^{LILAC}, τ^{LILAC}, R^{LILAC}

Mapping

Measurable parameters:

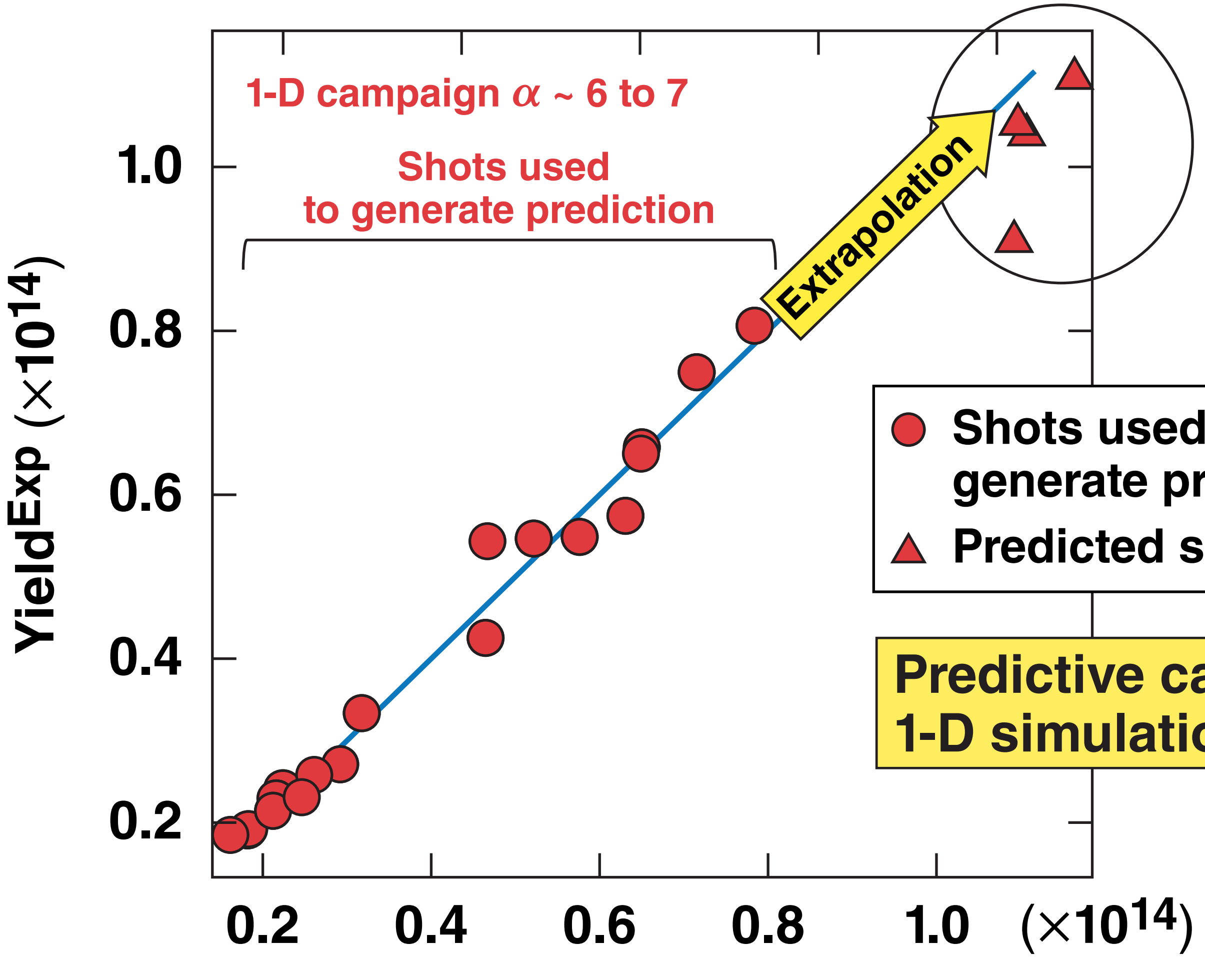
Yield^{Exp}, V_{imp}^{Exp}, ρR^{Exp}, T_i^{Exp}, τ^{Exp}, R^{Exp}

Example: Yield$^{Exp} = F\left(V_{imp}^{LILAC}, \rho R^{LILAC}, T_i^{LILAC}, \tau^{LILAC} \ldots\right)$ ← **New predictive capability** (also valid for 3-D systematic nonuniformities)

Instead of comparing each simulated parameter with its measured value, we map each measurement onto all simulated parameters through nonlinear correlations.

TC13680a

The combination of 1-D simulations and mapping relations provides a predictive capability as long as its validity can be extrapolated



Predictive capability:
1-D simulations + mapping relations

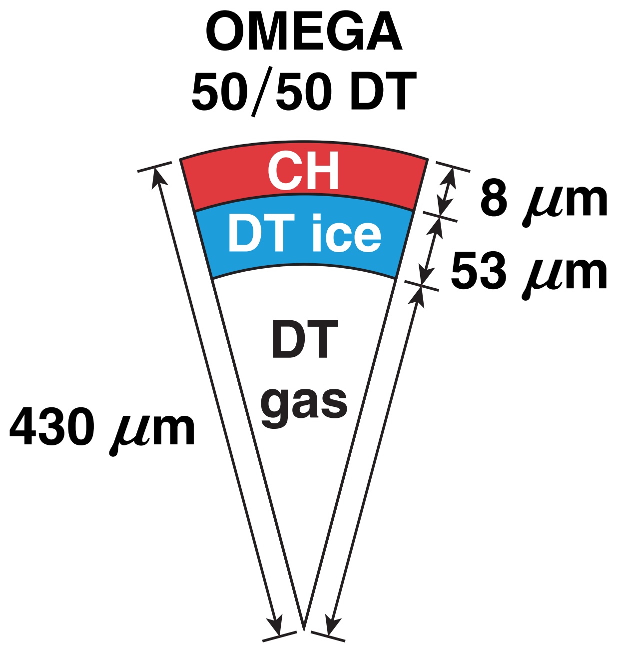
V_{imp}^{LILAC} = *LILAC* implosion velocity

M_{stag}^{LILAC} = *LILAC* stagnation mass

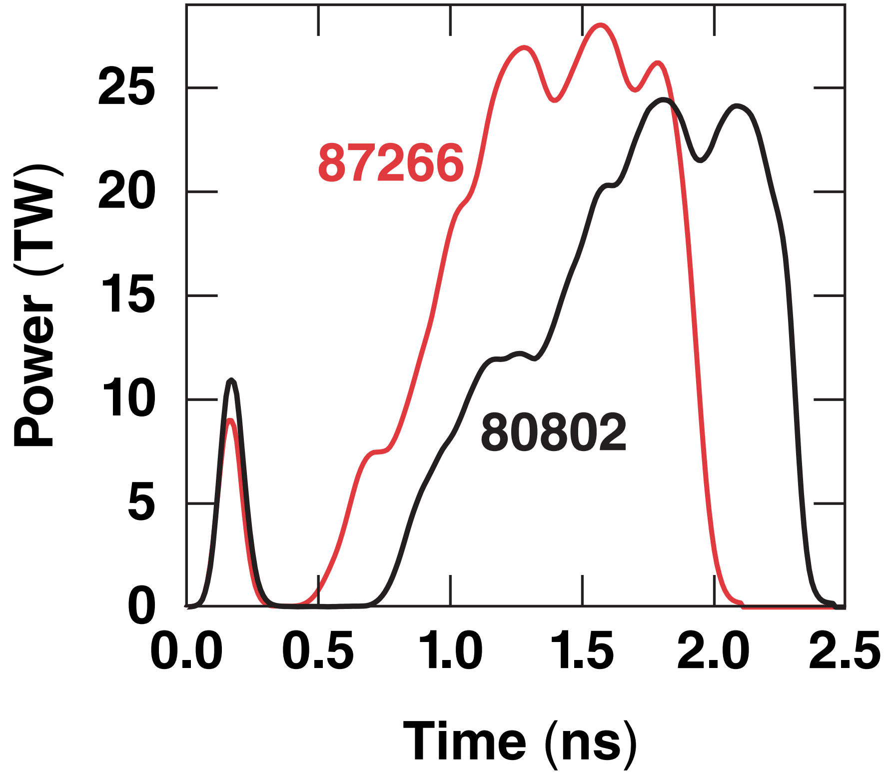
Mapping onto 1-D simulated parameters → $4.3 \times 10^{13} \left(\frac{V_{\text{imp}}^{LILAC}}{400}\right)^{4.17} \left(\frac{M_{\text{stag}}^{LILAC}}{0.01}\right)^{0.65}$

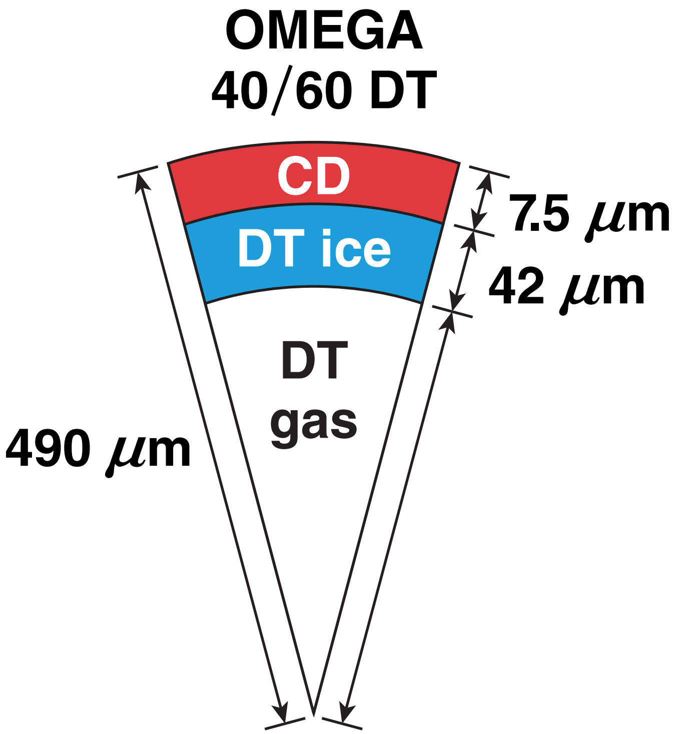
TC13681a

The higher yields were achieved through CD ablators, thinner ice, 40/60 DT mixture, modified pulse shapes, and larger diameter shells



80802
Y = 3.2 $\times 10^{13}$
ρR = 126 mg/cm^2
T_i = 2.6 keV

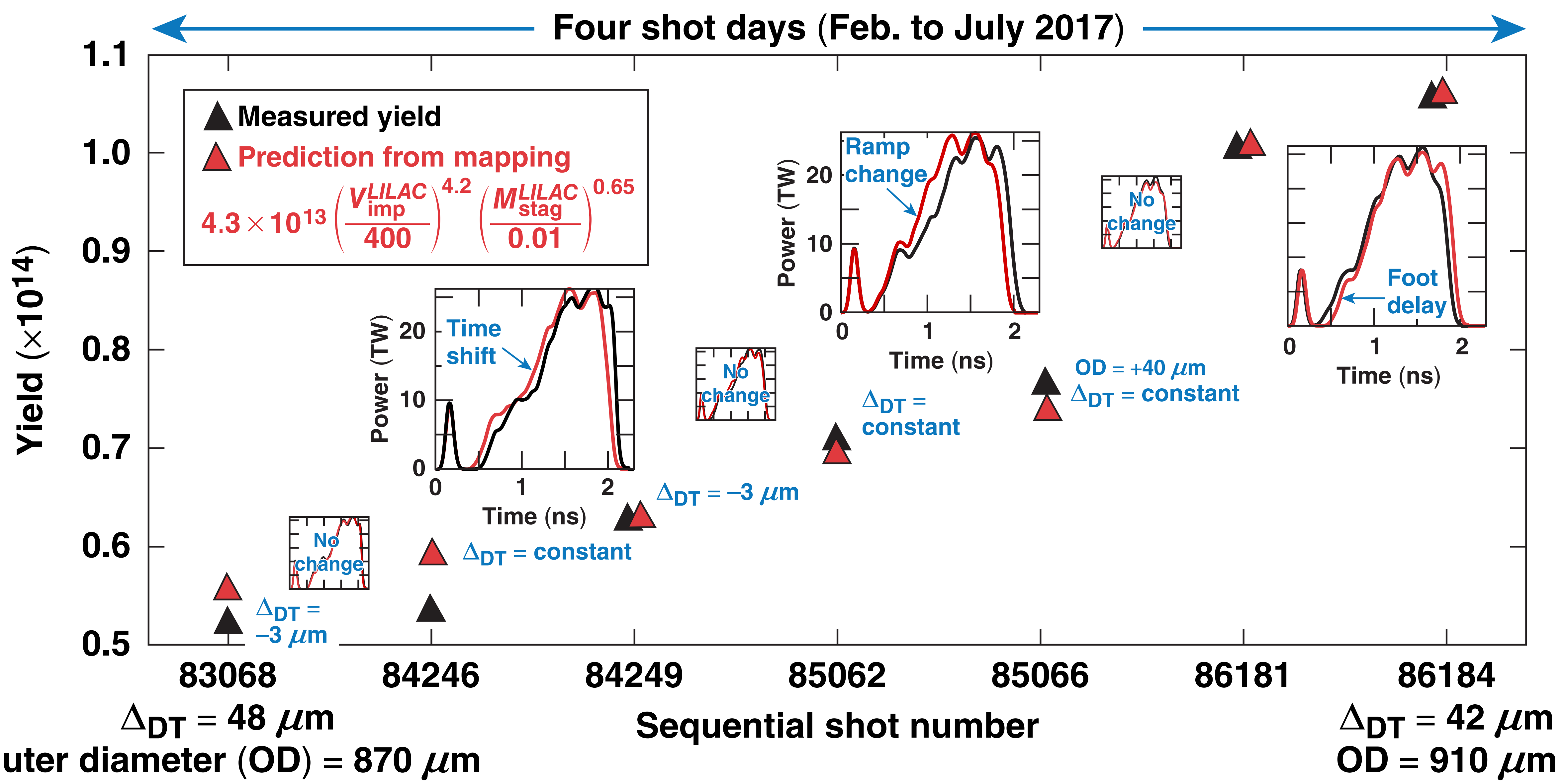




87258-69
Y = 1.2 to 1.4 $\times 10^{14}$
ρR = 110 to 130 mg/cm^2
T_i = 4.3 to 4.6 keV

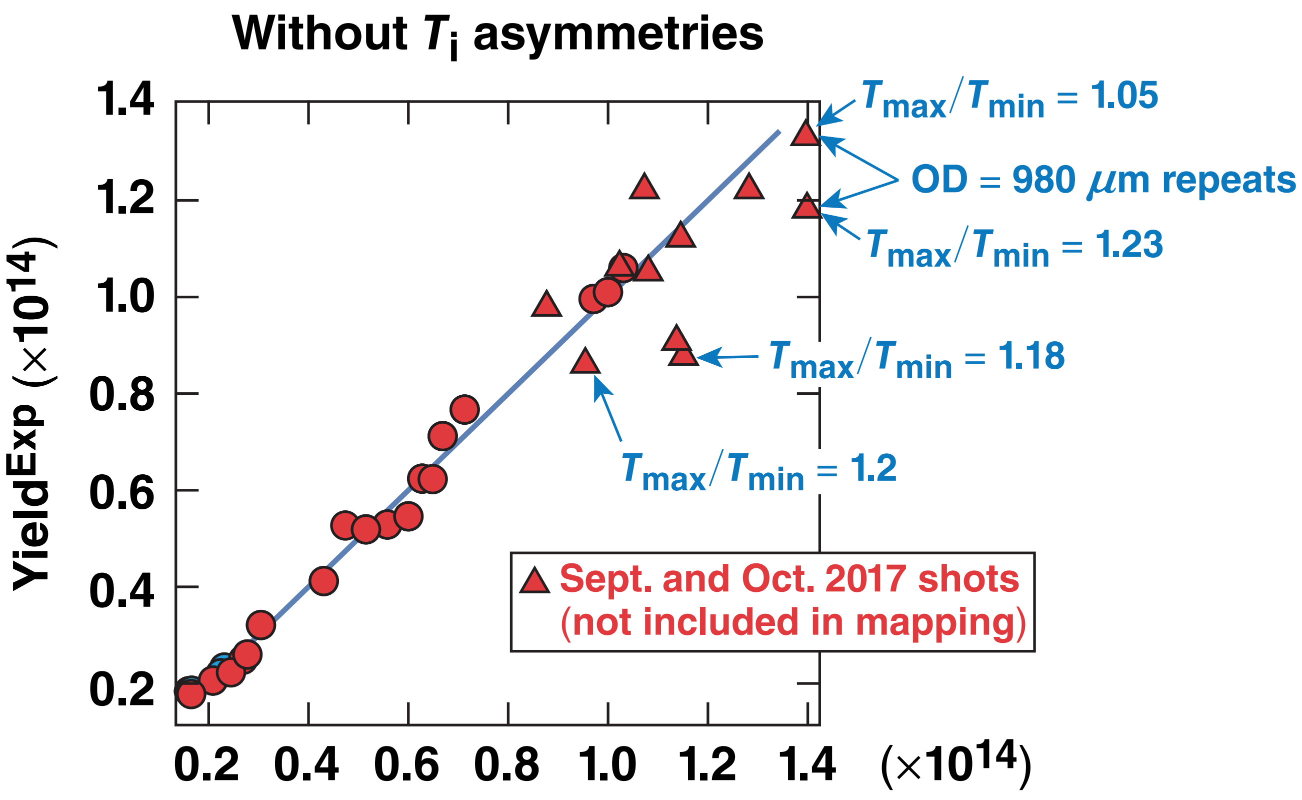
TC13687b

Systematic changes to the target specifications and laser pulse resulted in the expected increase in yield

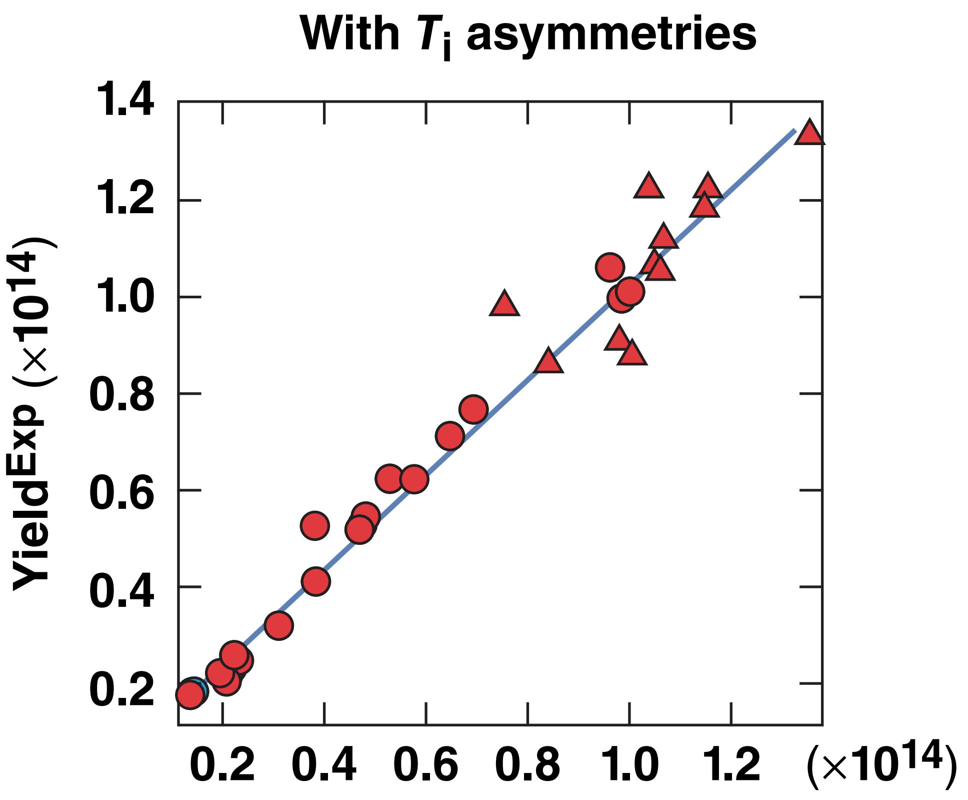


TC13688b

In the last two shot days (ten shots), an ~20% yield variability is observed between repeats and also between the measured yield and prediction of mapping model



$$4.3\times10^{13}\left(\frac{V_{imp}^{LILAC}}{400}\right)^{4.23}\left(\frac{M_{stag}^{LILAC}}{0.01}\right)^{0.85}$$



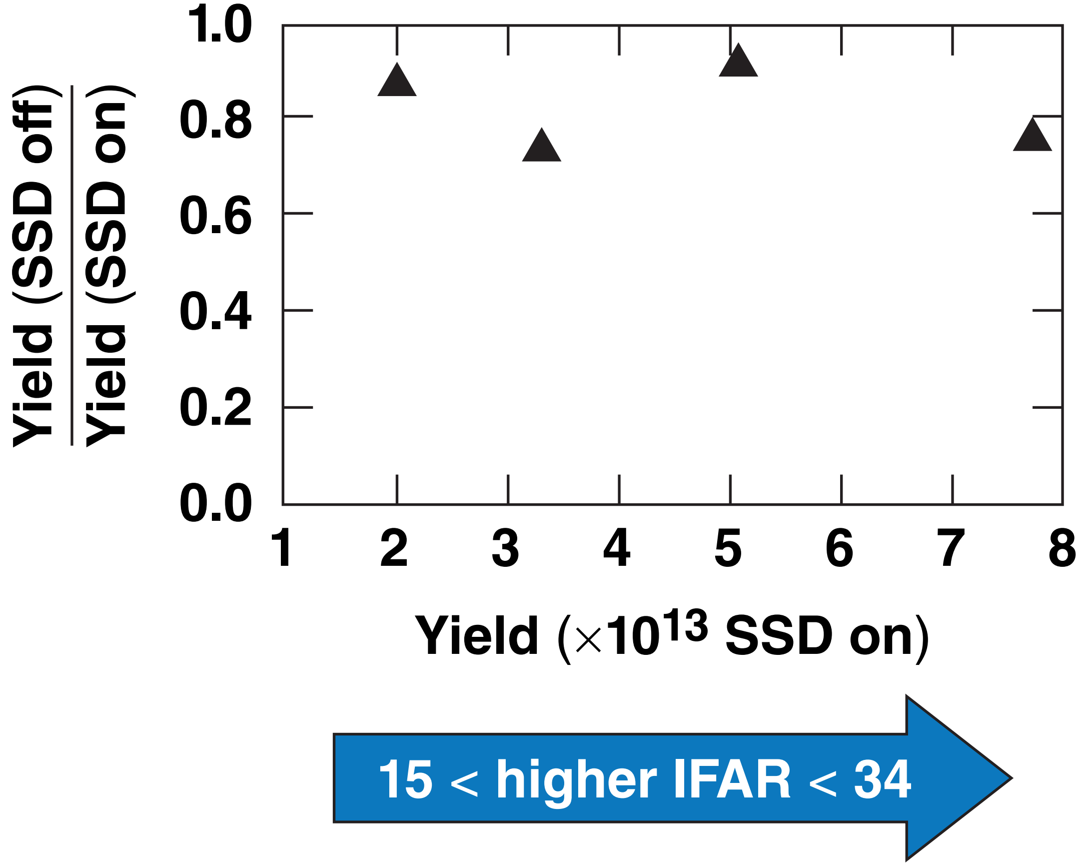
$$4.7\times10^{13}\left(\frac{V_{imp}^{LILAC}}{400}\right)^{4}\left(\frac{M_{stag}^{LILAC}}{0.01}\right)^{0.7}\left(\frac{T_{min}}{T_{max}}\right)$$

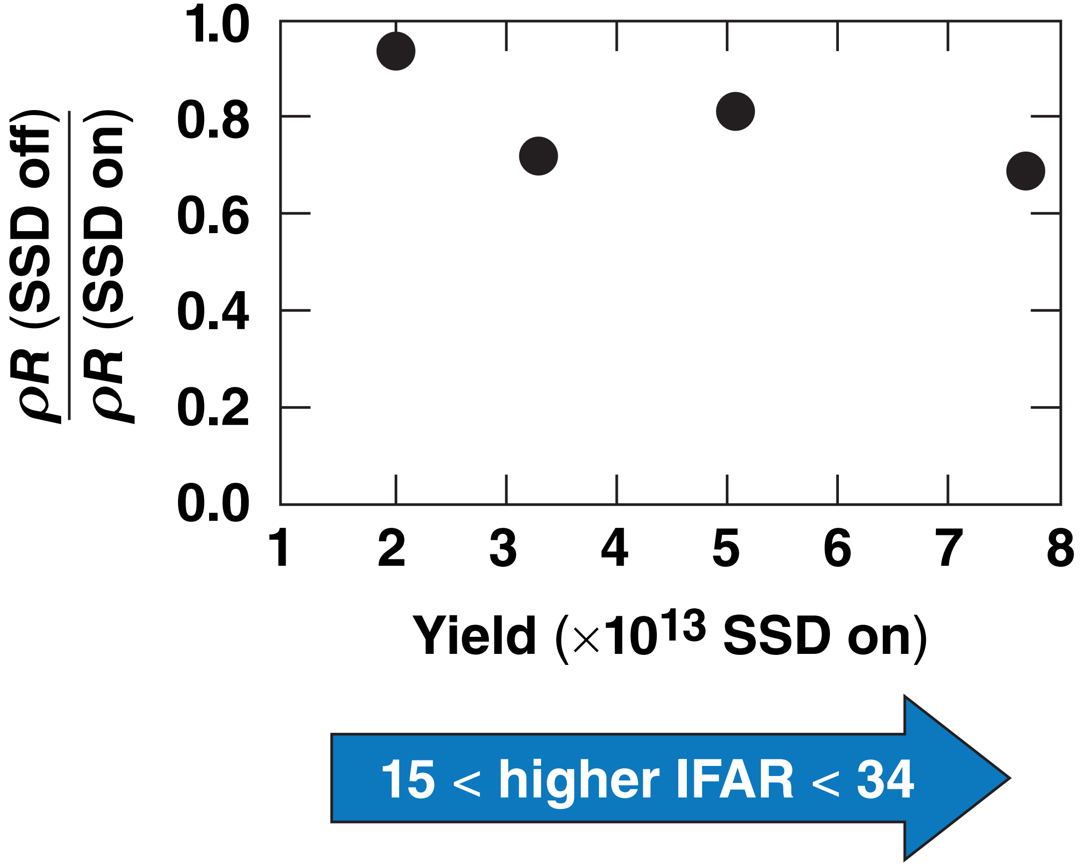
Large temperature asymmetries suggest nonsystematic distortions possibly caused by the large DT ice rms (~1.5 μm) or target offsets.

TC13940

What are the Results Telling Us?

Hydro stability SSD on/off tests show modest degradation in performance but no proximity to a stability cliff



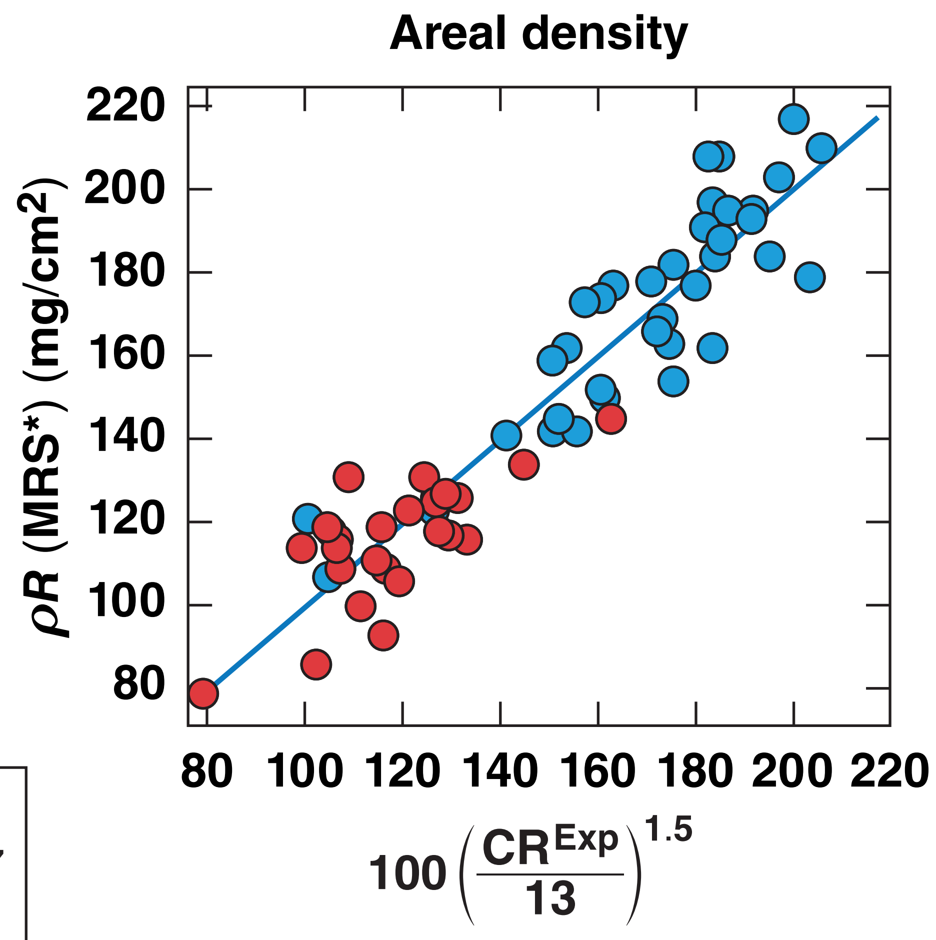


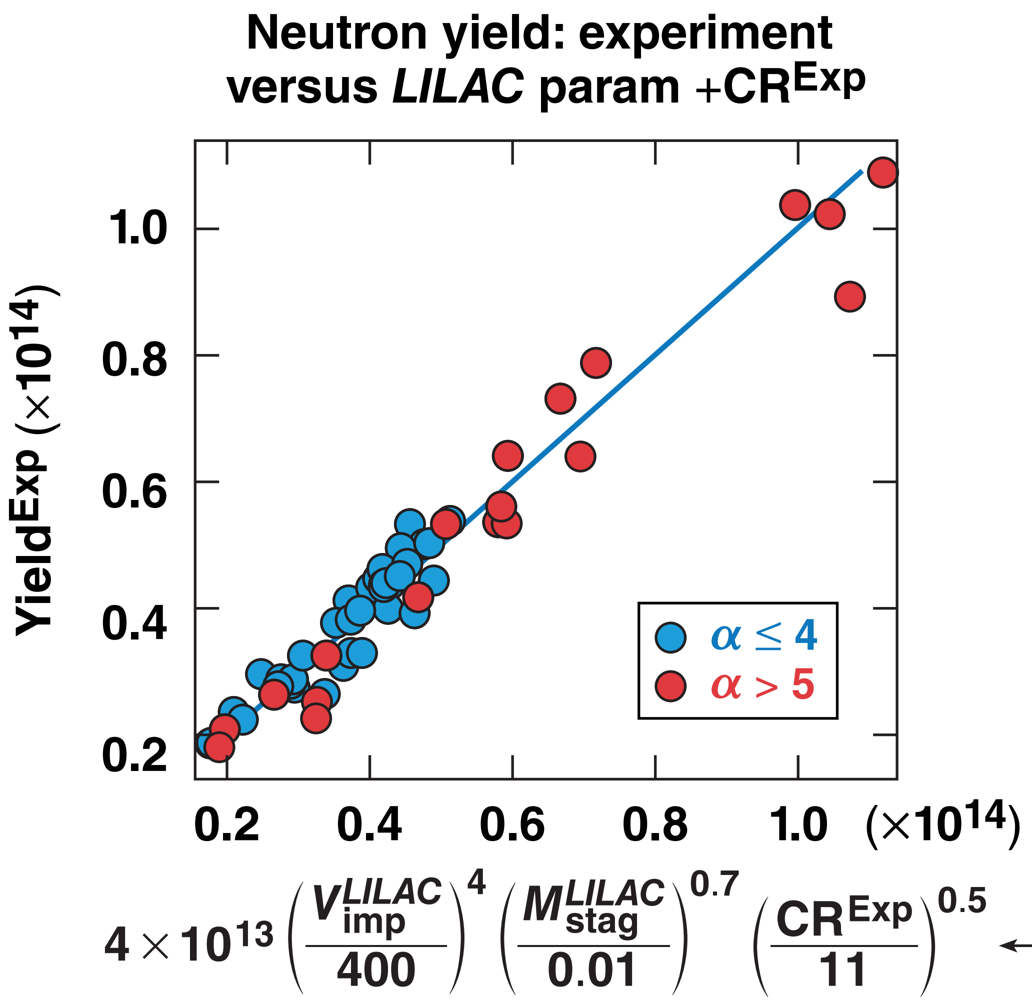
TC13685a

Including lower-adiabat implosions shows the yield increase from convergence is less than 1-D predictions while the areal density scales as 1-D

1-D theory

$$100\left(\frac{CR}{13}\right)^{1.7}$$





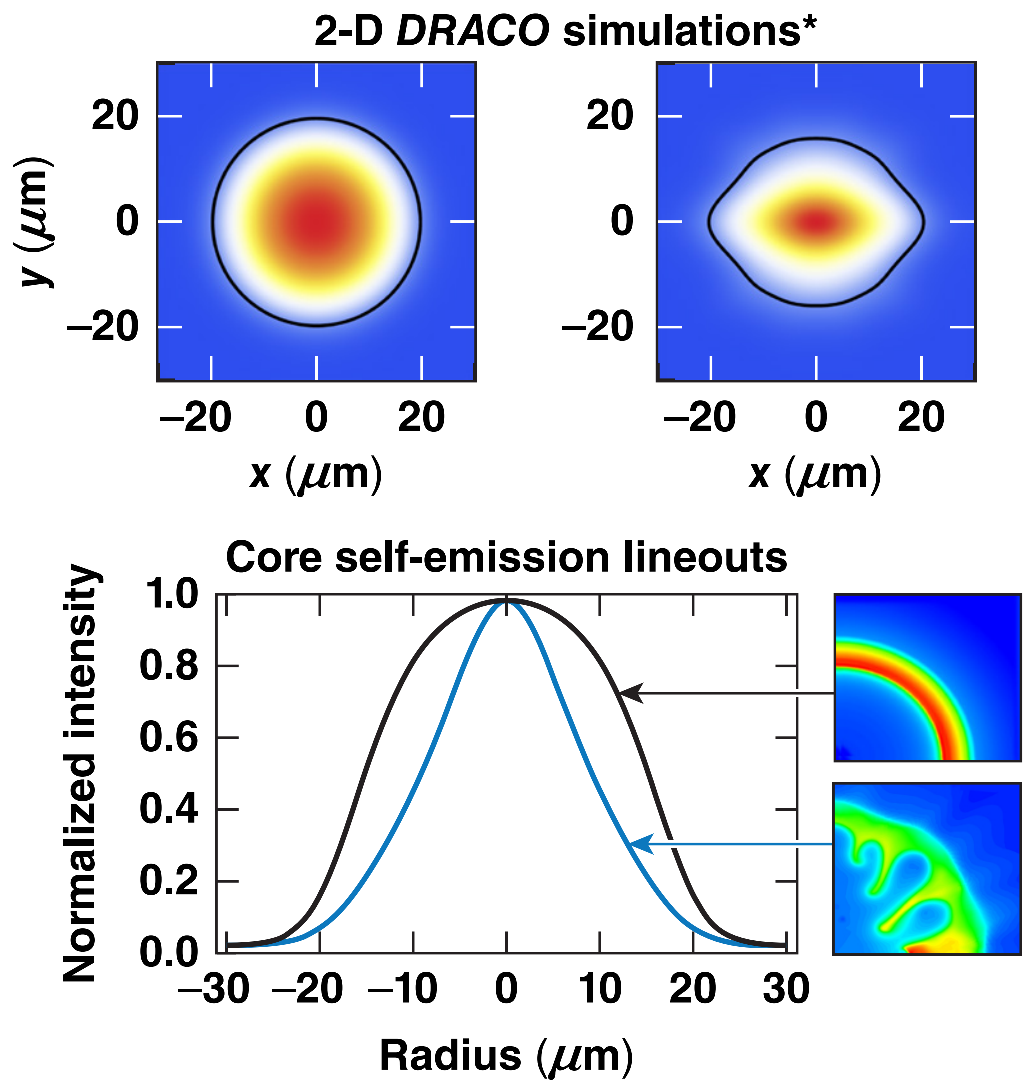
1-D theory
CR^2

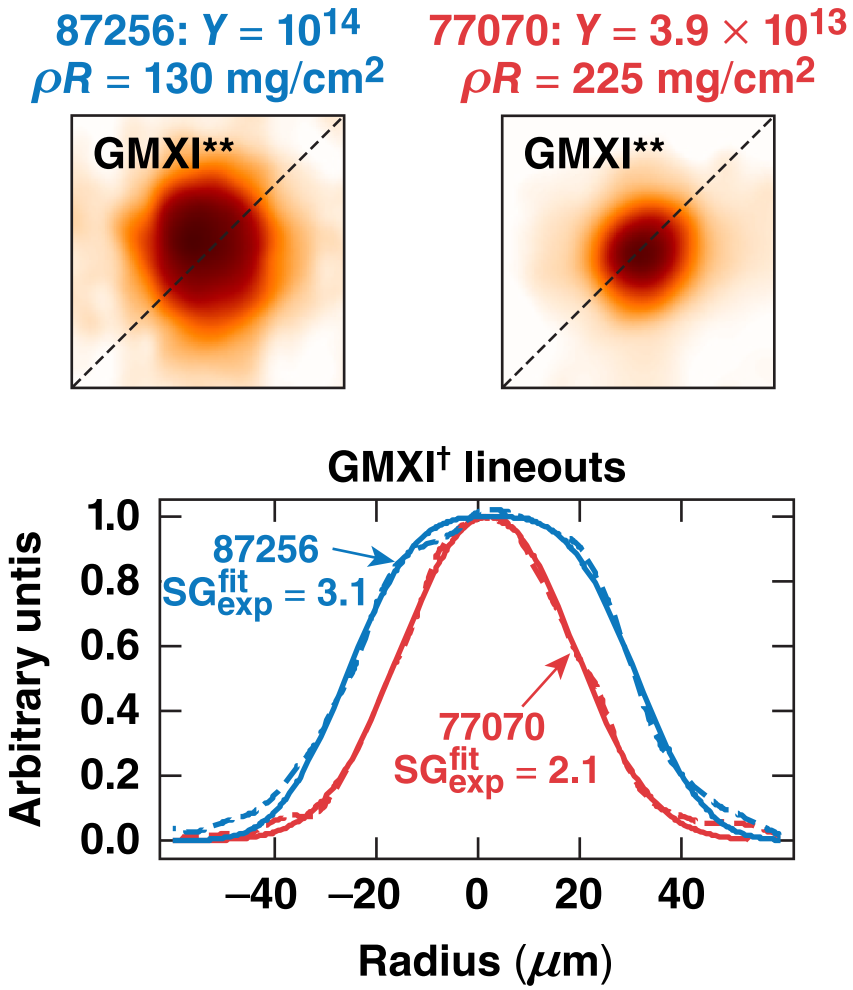
In experiments, a higher CR leads to a very modest increase in yield.

*MRS: magnetic recoil spectrometer

TC13739a

The shape of the hot-spot self-emission profile is used as a measure of proximity to 1-D behavior; the 1-D Campaign targets are more "1-D" than high-CR targets





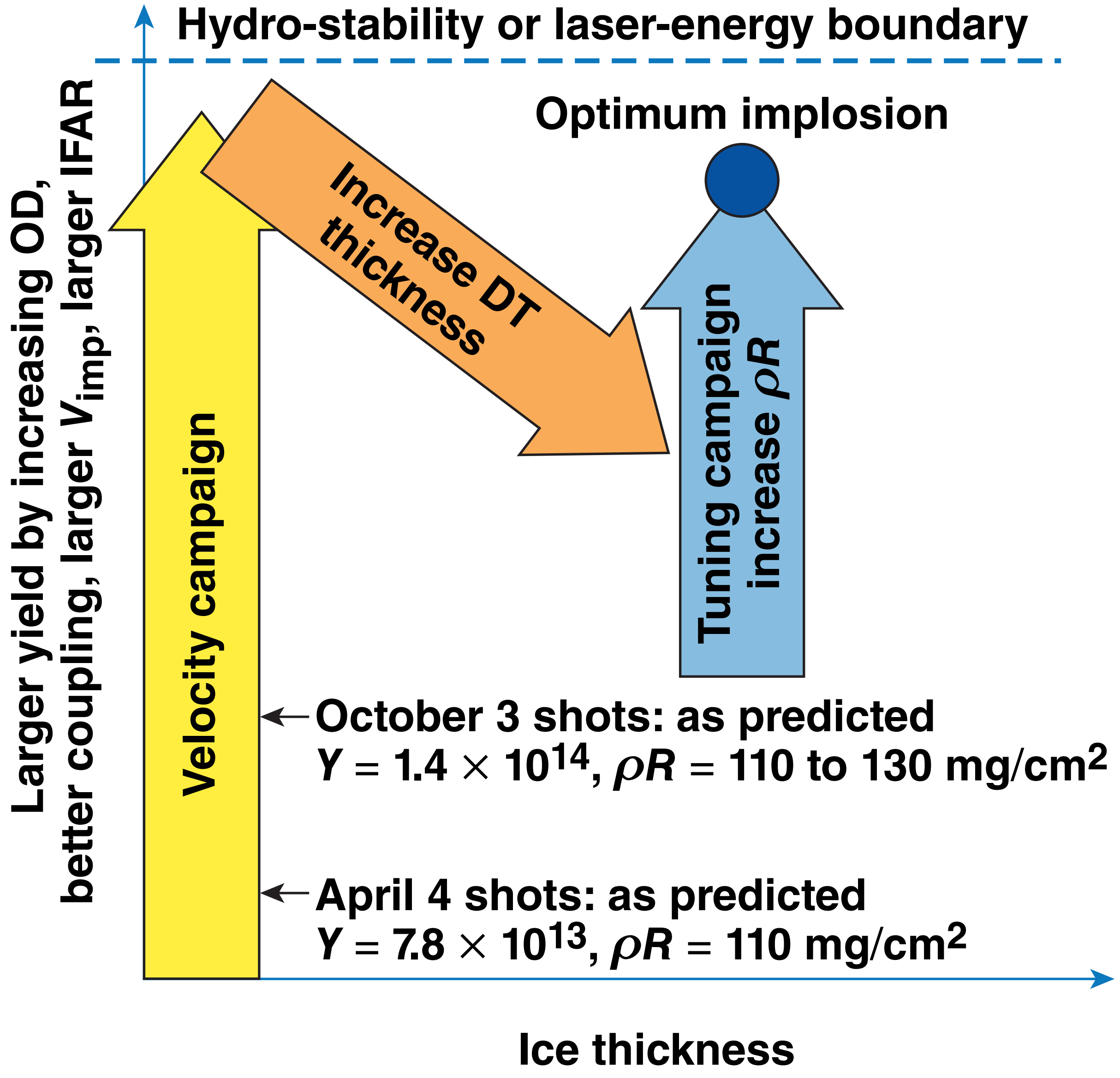
*R. Nora, Laboratory for Laser Energetics, private communication (2014).
**F. J. Marshall and J. A. Oertel, Rev. Sci. Instrum. 68, 735 (1997).
†GMXI: gated monochromatic x-ray imager

TC13094a

OMEGA Roadmap and Extrapolation to NIF* Laser Energies

*NIF: National Ignition Facility

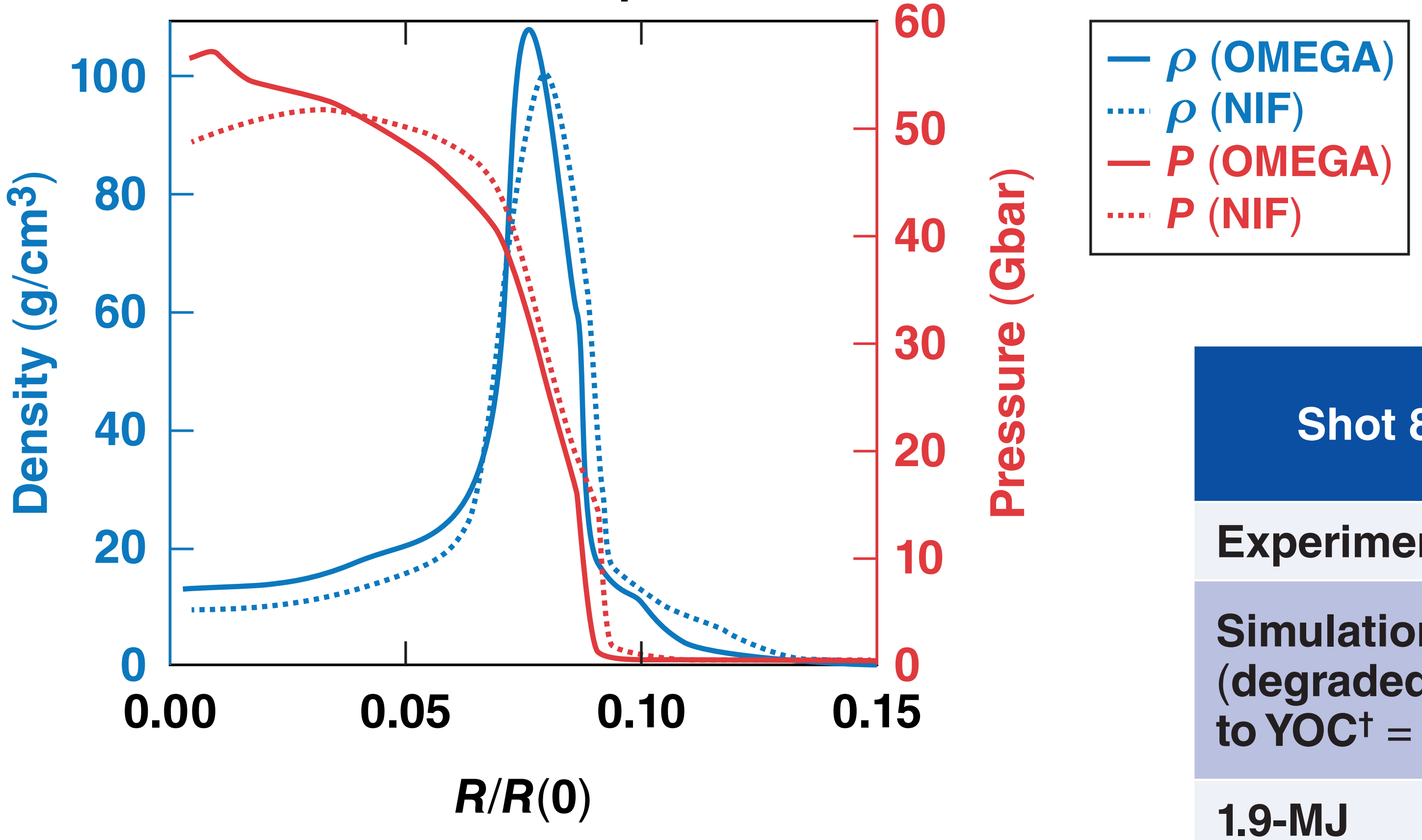
A systematic approach is being used to find the optimum implosion on OMEGA



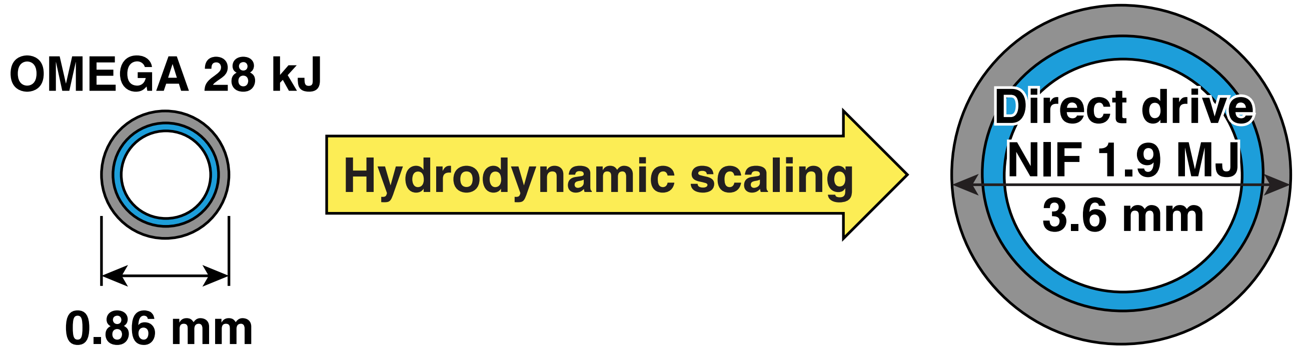
TC13691a

OMEGA highest-yield shots extrapolate to fusion yields $\gtrsim$230 kJ at 1.9 MJ of symmetric illumination

1-D profiles from OMEGA/NIF-symmetric used in the extrapolation



- Hydro-equivalent extrapolation*
  V_{imp} = const, α = const, mass ~ volume ~ E_L



Shot 87026	T_i (keV)	R_{17} (μm)	τ (ps)	$\langle P \rangle$ (Gbar)	Yield
Experiment	4.08	34.5	79	40	1.1×10^{14}
Simulation (degraded** in 2-D to YOC† = 0.75)	4.01	34.0	74	43	1.1×10^{14}
1.9-MJ extrapolation	5.3 4.9 no α	143	300	51	8.2×10^{16} 230 kJ

*R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).
**A. Bose *et al.*, Phys. Plasmas 24, 102704 (2017).
†YOC: yield-over-clean

TC13856

High-adiabat ($\alpha \approx 6$ to 7) implosions achieved the highest fusion yields of 1.4×10^{14} on OMEGA with high predictability using a statistical mapping model

UR LLE

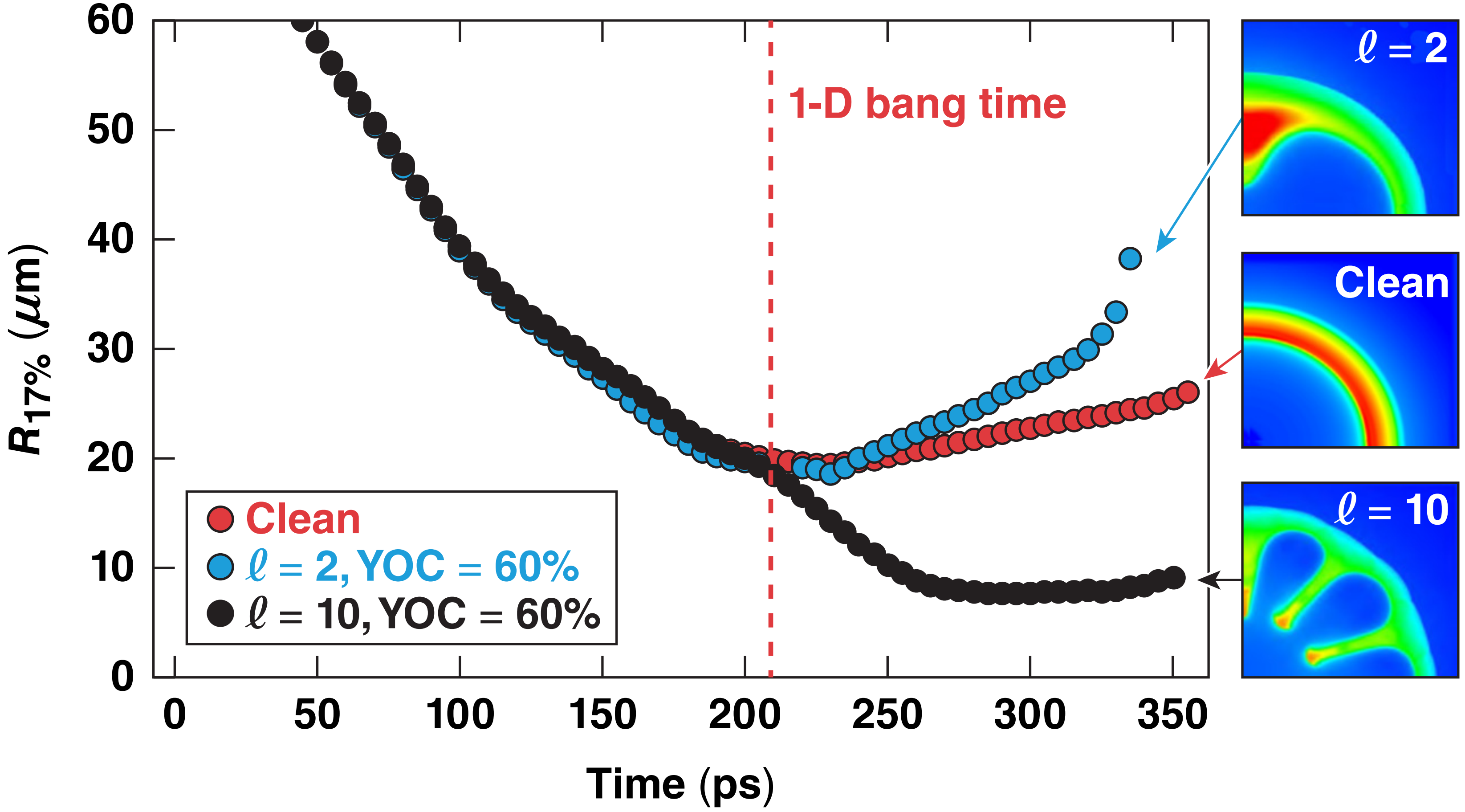
- The ongoing 1-D campaign is building an experimental database of high-adiabat, low-convergence implosions (CR* ~ 12 to 14)
- By mapping the experimental results onto the simulation database, an accurate predictive tool is developed that enables the design of targets with improved performance
- The highest fusion yield of 1.4×10^{14} is achieved by increasing the target outer diameter and reducing the DT ice thickness
- Based on these recent results, a roadmap is being developed to find the optimum target and laser pulse
- Hydro-equivalent extrapolation to 1.9 MJ symmetric illumination shows fusion yields $\geq$230 kJ for best performing implosions

*CR: convergence ratio

Backup

The time history of the hot-spot radius $R_{17\%}$ monitors deviations from 1-D behavior

- Low modes (ℓ ~2) increase the hot-spot size
- Intermediate modes (ℓ ~10) decrease the size



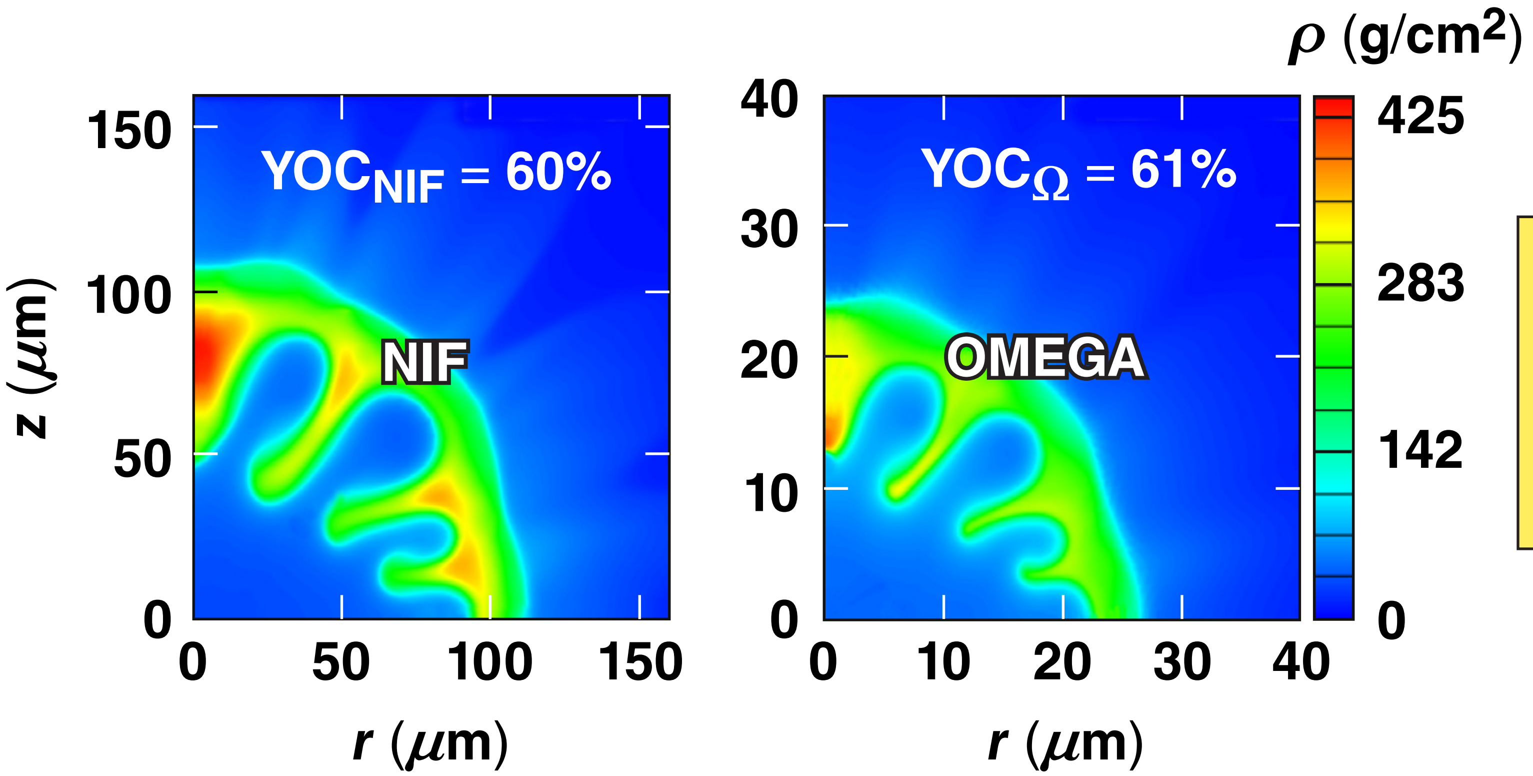
The time history of the hot-spot radius reveals which modes are dominant.

* A. Bose, R. Betti, and D. Shvarts, JO7.00007, this conference.

TC13093

The hydrodynamic scaling holds in three dimensions

- In-flight scaling: $R \sim E_L^{1/3}$ $P_L \sim E_L^{2/3}$ $\tau_{pulse} \sim E_L^{1/3}$
  $V_{imp} \sim$ const $\alpha \sim$ const RT growth factors ~ const
- Stagnation scaling: $P \sim$ const $T \sim R^{0.2}$ $V_{hs} \sim R^3$
  $\tau_{burn} \sim R$ $\rho R_{tot} \sim R$



$$\mathrm{Yield}_{no\,\alpha} \sim E_L^{1.45}$$

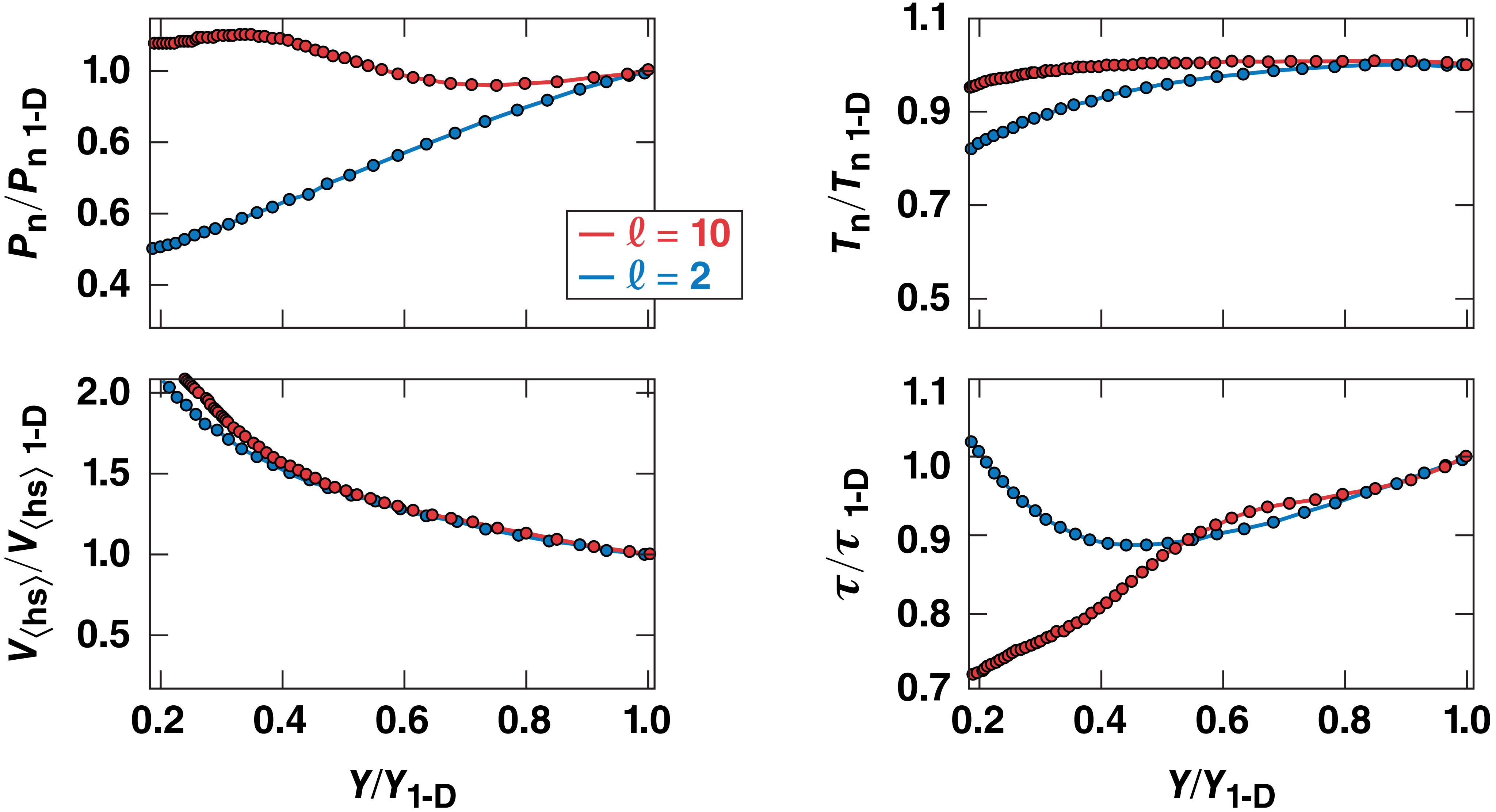
$$\chi_{no\,\alpha} \sim E_L^{0.35}$$

$$\frac{Y_\alpha}{Y_{no\,\alpha}} \approx \frac{1}{(1-1.04\,\chi_{no\,\alpha})^{0.75}}$$

A. Bose *et al*., Phys. Plasmas 22, 072702 (2015);
R. Nora *et al*., Phys. Plasmas 21, 056316 (2014).

TC10975e

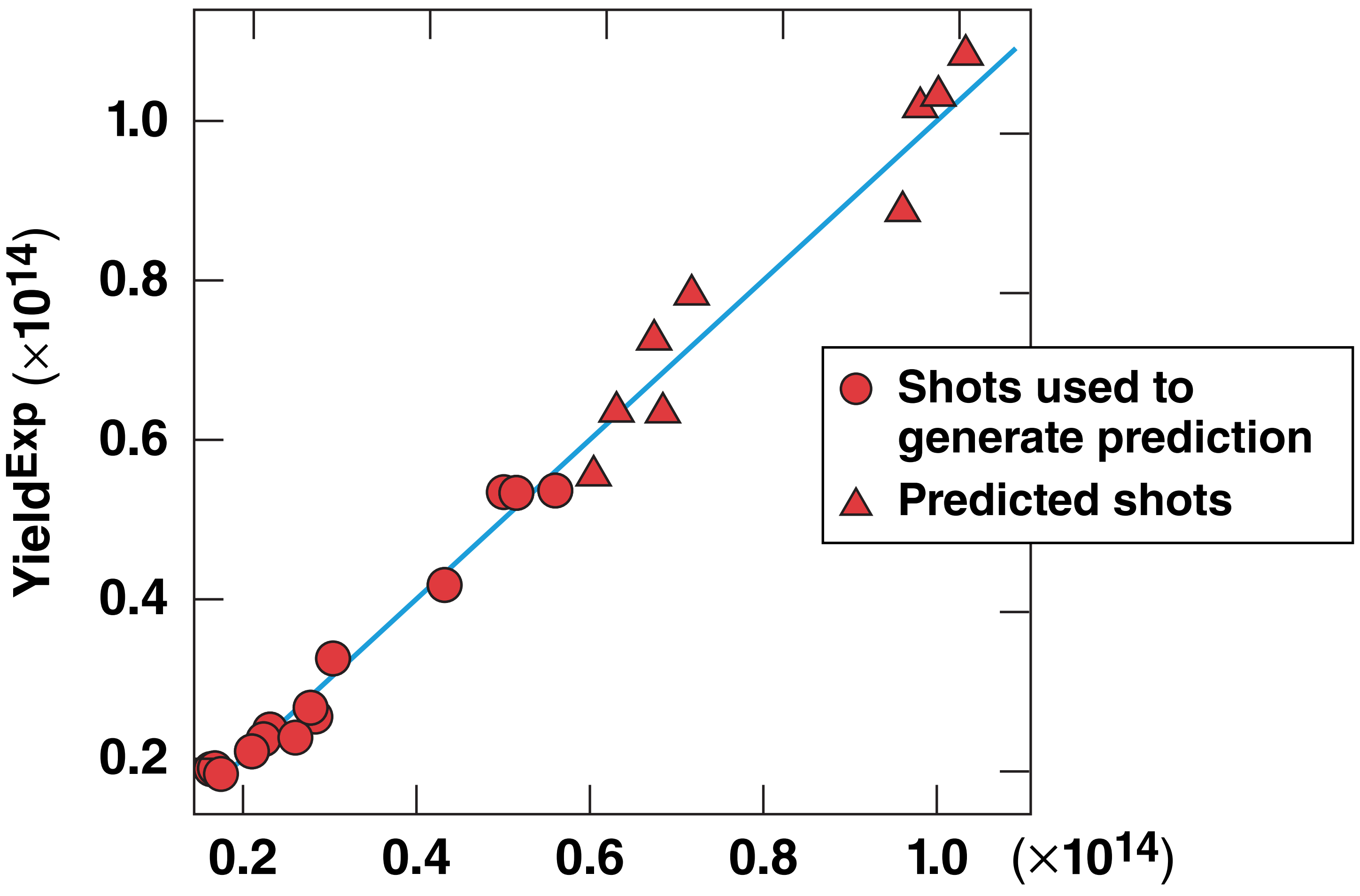
The hydro-equivalent extrapolation uses the results of 1-D simulations combined with 2-D degradation to match the experimental observables



TC13250

*A. Bose, Ph.D. thesis, University of Rochester, 2017; A. Bose *et al.*, Phys. Plasmas 24, 102704 (2017).

The yield predictive capability of the mapping relations applies over a wide range of extrapolations



$$4.3\times10^{13}\left(\frac{V_{imp}^{LILAC}}{400}\right)^{4.03}\left(\frac{M_{stag}^{LILAC}}{0.014}\right)^{0.69}$$

TC13682a

The yield's unique dependence on 1-D simulated parameters persists in 3-D as long as the 3-D dynamics are affected by dominant systematic nonuniformities

- $Y_{exp} = Y_{1\text{-}D}$ (1-D parameters) YOC (distortion)
- A_0 = initial nonuniformities (target and/or laser)
- f (1-D) = amplifications of distortion caused by implosion (RT, RM*, BP**)
- $\text{YOC} = \text{YOC}\left[\tilde{A}_0^{\text{systematic}} f_s\,(\text{1-D}) + \tilde{A}_0^{\text{random}} f_r\,(\text{1-D})\right]$
- If systematic nonuniformities are dominant: $\tilde{A}_0^{\text{systematic}} \gg \tilde{A}_0^{\text{random}}$
- $Y_{exp} = Y_{1\text{-}D}\,(\text{1-D parameters})\,\text{YOC}\left[\tilde{A}_0^{\text{systematic}} f_s\,(\text{1-D parameters})\right]$
- If $\tilde{A}_0^{\text{systematic}}$ = constant, the yield depends only on 1-D parameters even in distorted implosions

$Y_{exp} = Y_{1\text{-}D}$ (1-D parameters)

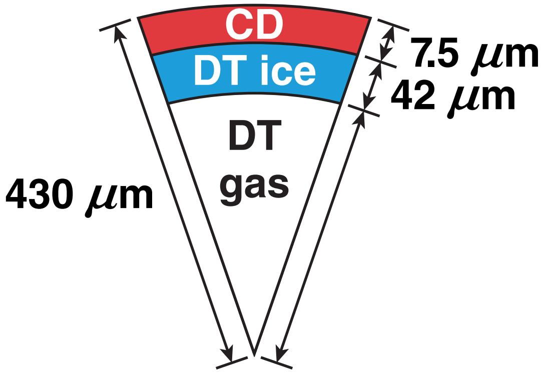
For 1-D implosions or 3-D with dominant systematic nonuniformities

*RM: Richtmyer–Meshkov
**BP: Bell–Plesset

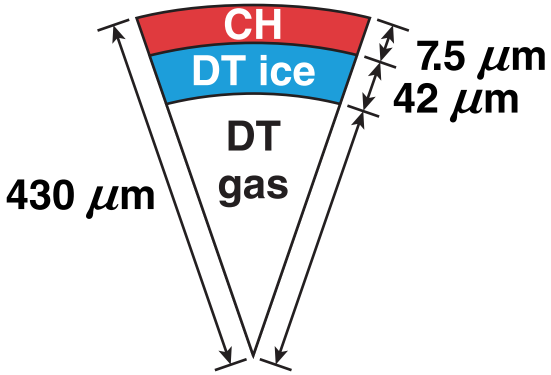
TC13683a

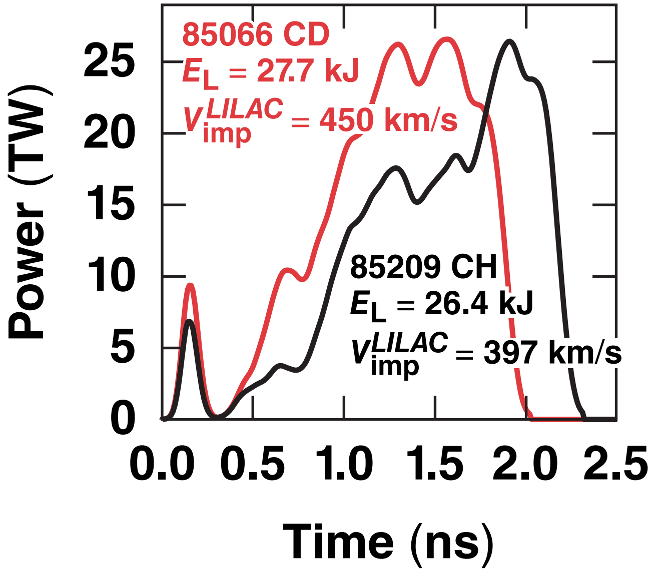
A convergence test on the thin 42-μm ice targets did not show proximity to stability cliffs for low and mid modes

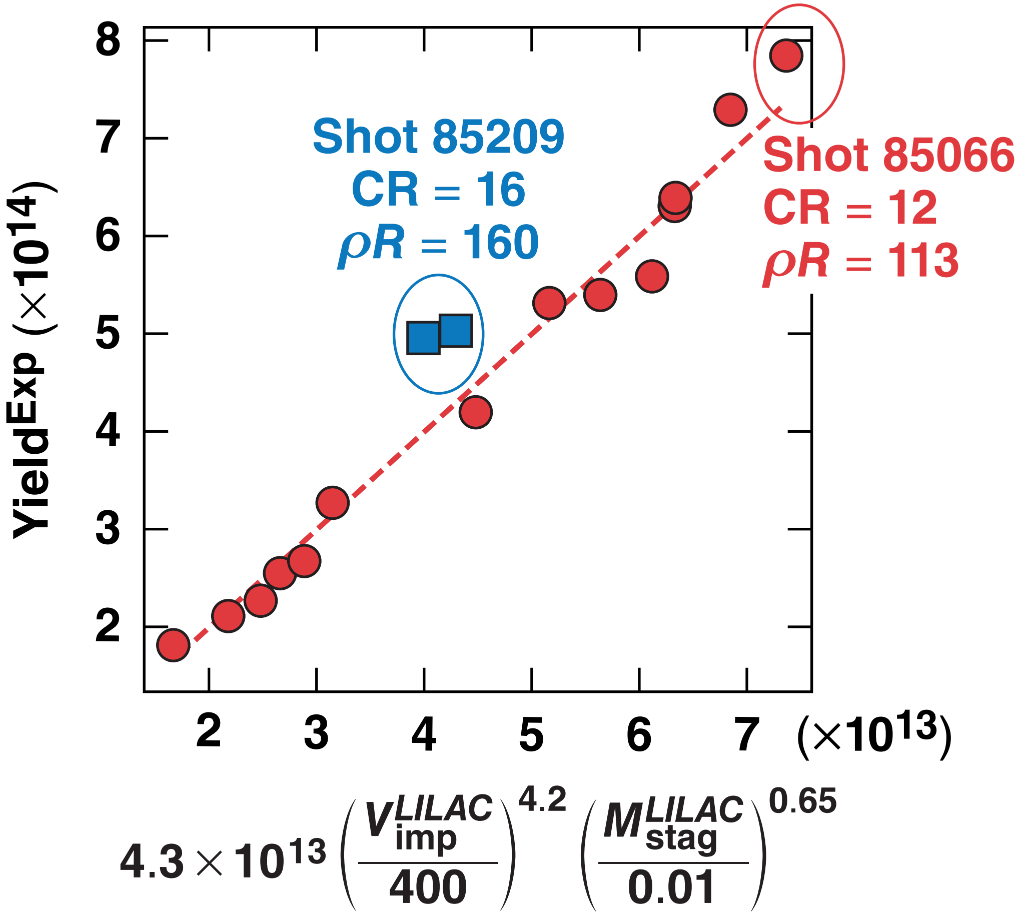
85066 CR = 12



85209 CR = 16



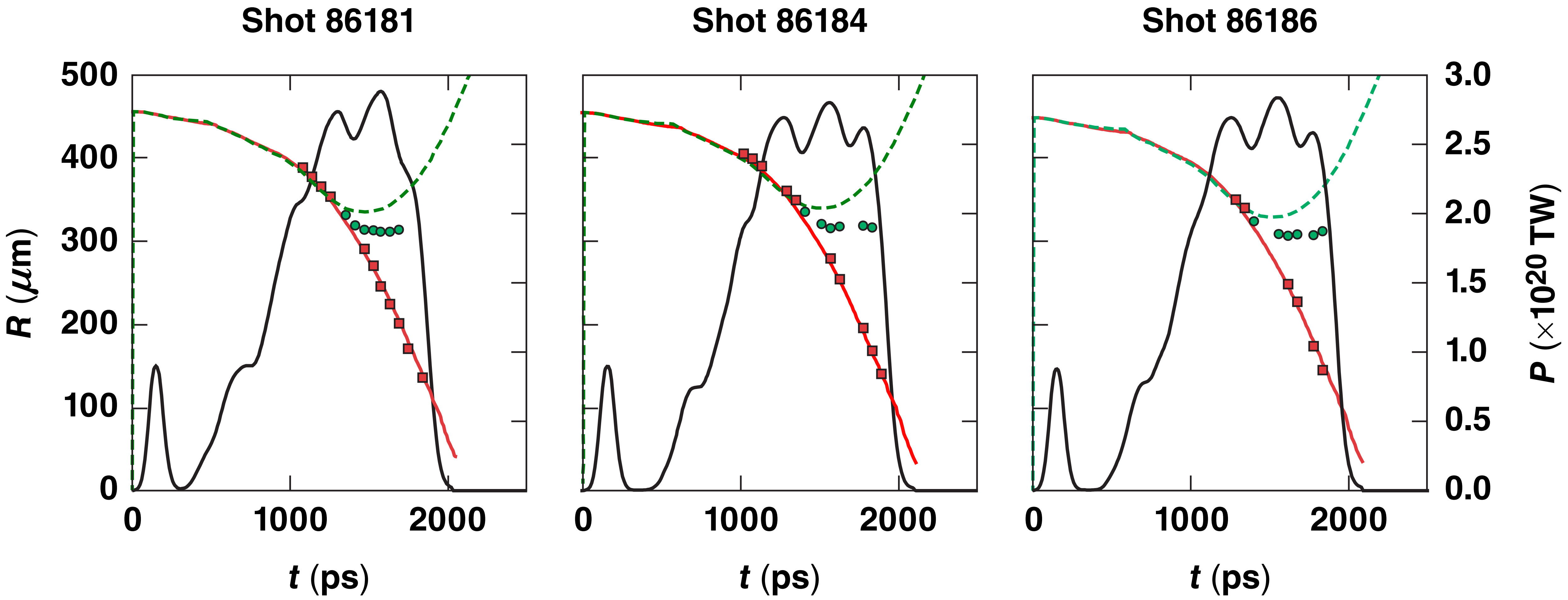




Higher-CR targets performed better than low-CR targets at the same predicted velocity.

TC13686a

Simulated trajectories compare favorably with experimental measurements



TC13725a