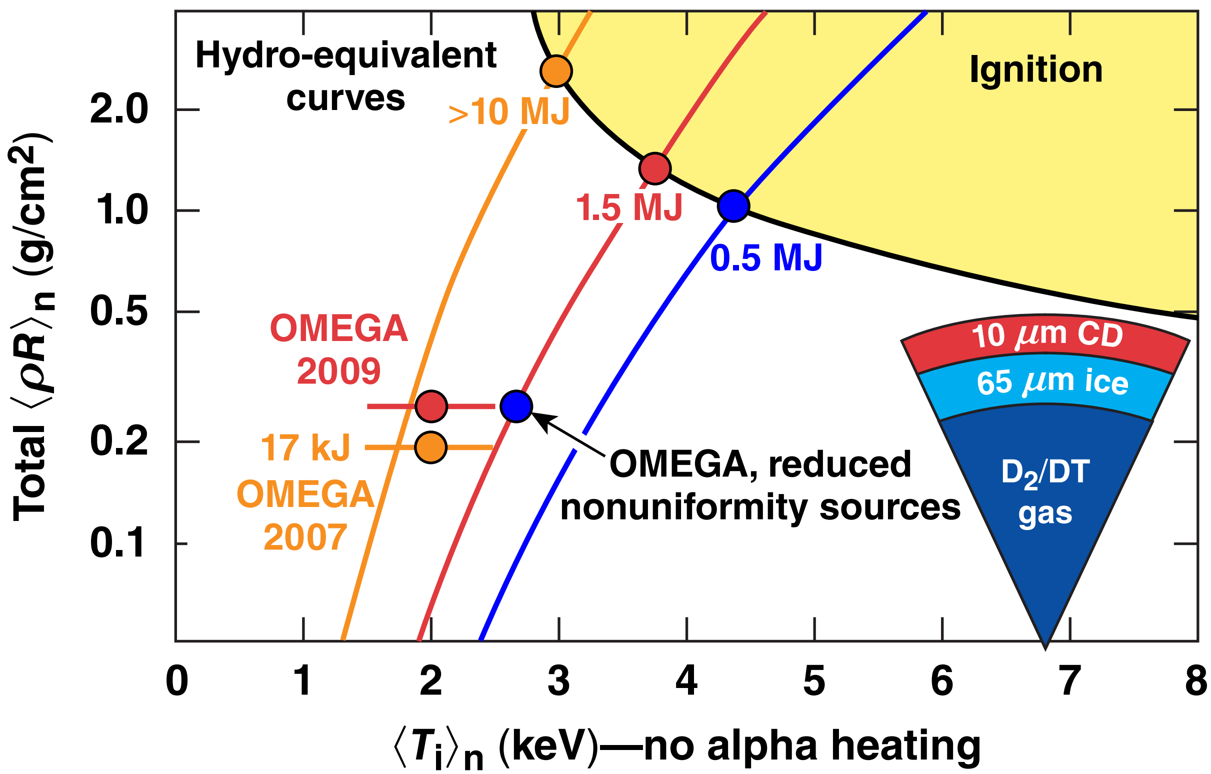
Low-Adiabat, High-Compression Cryogenic Deuterium–Tritium Implosions on OMEGA



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Summary

OMEGA experiments are used to validate theoretical hydrodynamic scaling for ρR, $<T_i>_n$, and yield used in calculating ignition factor

- The ignition factors (ITF, ITFX, χ) define in-flight shell (V_{imp}, α) and hot-spot conditions for achieving ignition
- Current simulations are in agreement with experimental measurements of $<\rho R>_n$, $<T_i>_n$, yield, and bang time
- Cross-beam transfer is important for understanding experimental results
- A model has been developed to relate the hot-spot distortion fraction with reduction in T_i and yield

Collaborators

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Outline

- Ignition design and ignition conditions
- Areal density
  - shock tuning
  - control of short-wavelength perturbation growth
- Hot-spot ion temperature and yield
  - validation of drive efficiency
  - effect of perturbation growth

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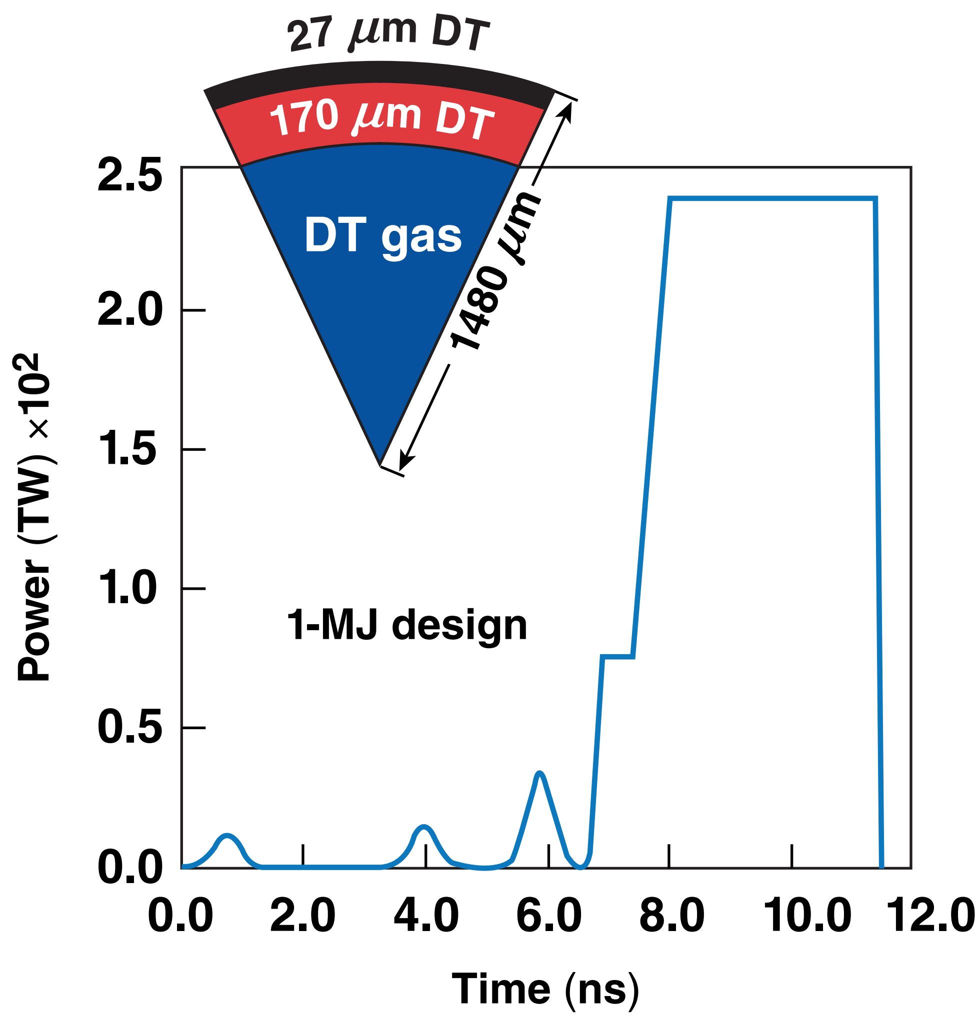
The symmetric direct-drive NIF ignition design has a 1-D gain of ~50



E_L = 1 to 1.5 MJ
V_{imp} = 3.5 to 4 × 10^7 cm/s
IFAR = 35 to 45
$Gain_{1\text{-}D}$ = 45 to 50

TC9010

The ignition factors depend on shell conditions and fuel mix

- Ignition threshold factor for the indirect-drive NIF design[1]

$$\mathrm{ITF} \sim V_{\mathrm{imp}}^{8}\,\alpha^{-4}\,(1-1.2\xi)^{4}\left(\frac{M_{\mathrm{clean}}}{M_{\mathrm{DT}}}\right)^{0.5}$$

$$\alpha = \frac{P}{P_{\mathrm{FERMI}}}$$

ξ = hot-spot distortion fraction

M_{DT} = fuel mass

ITF = 1 has a 50% probability of achieving ignition

- Threshold factor[2]: measured conditions at neutron-production time

$$\chi = \langle \rho R \rangle^{0.8}\left(\frac{\langle T_{\mathrm{i}} \rangle}{4.7\ \mathrm{keV}}\right)^{1.6}\mathrm{YOC}^{0.5}$$

$\chi > 1$ required for ignition

- ITFX ~ χ^{3} (defined in Ref. 3)

One of the main goals of the cryogenic campaign on OMEGA is to validate modeling of $\langle \rho R \rangle$, $\langle T_{\mathrm{i}} \rangle$, and yield.

[1] S. Haan *et al.*, "Point Design Targets, Specifications, and Requirements for the 2010 Ignition Campaign on the National Ignition Facility," submitted to Phys. Plasmas
[2] R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).
[3] B. K. Spears *et al.*, J. Phys., Conf. Ser. 244, 022014 (2010).

TC9011

Outline

- Ignition design and ignition conditions
- Areal density
  - shock tuning
  - control of short-wavelength perturbation growth
- Hot-spot ion temperature and yield
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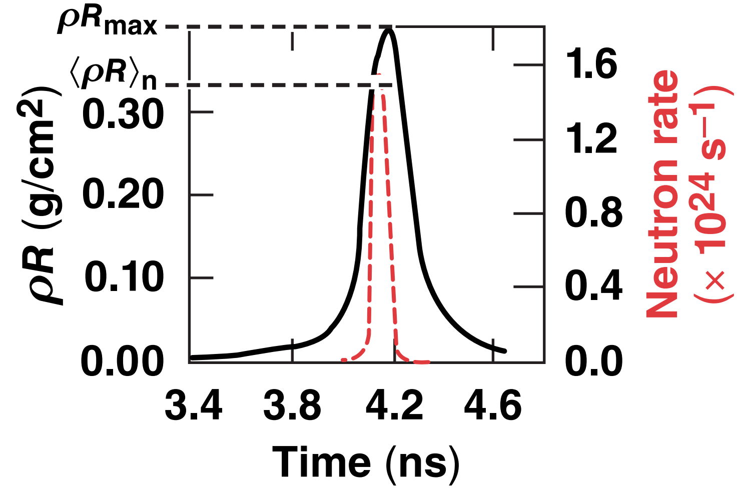
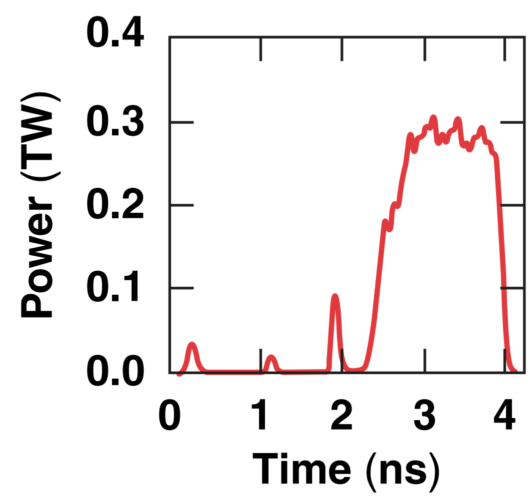
The shell areal density depends mainly on shell adiabat[1]

$$\langle \rho R \rangle_n = 1.7 \frac{E_{L,\mathrm{MJ}}^{1/3}}{\alpha_{\mathrm{if}}^{0.54}}$$

- Shell adiabat is determined by
  - shock heating—optimized in triple-picket design
  - excessive short-scale perturbation growth—controlled by shell IFAR = radius/shell thickness

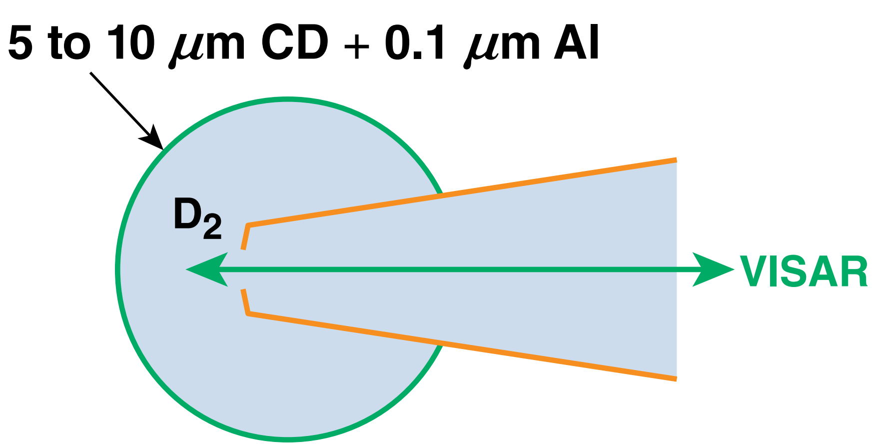




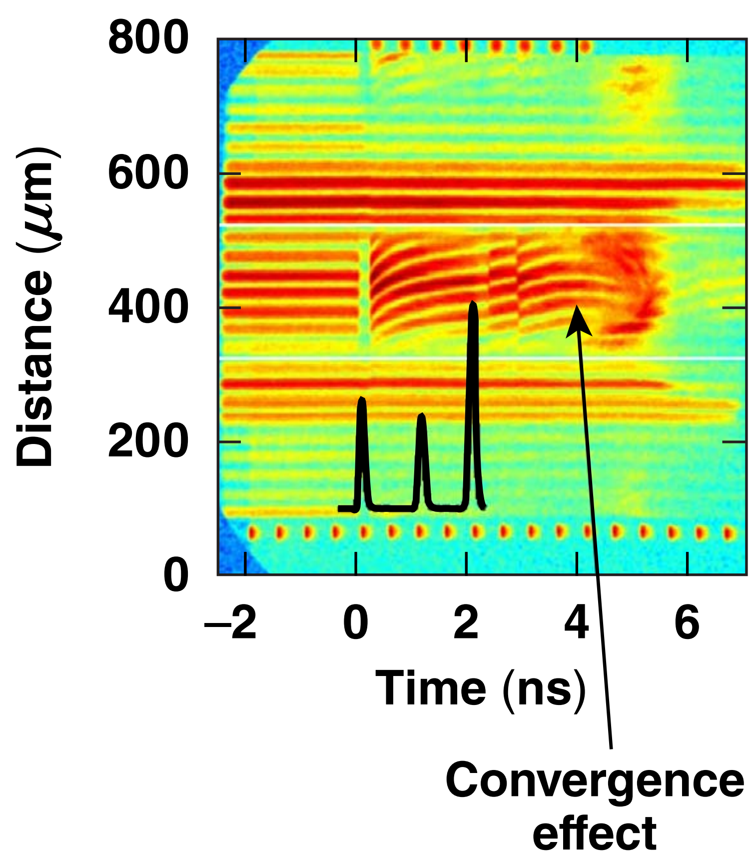
TC9013

[1] C. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

Shock tuning is performed using VISAR measurements[1]



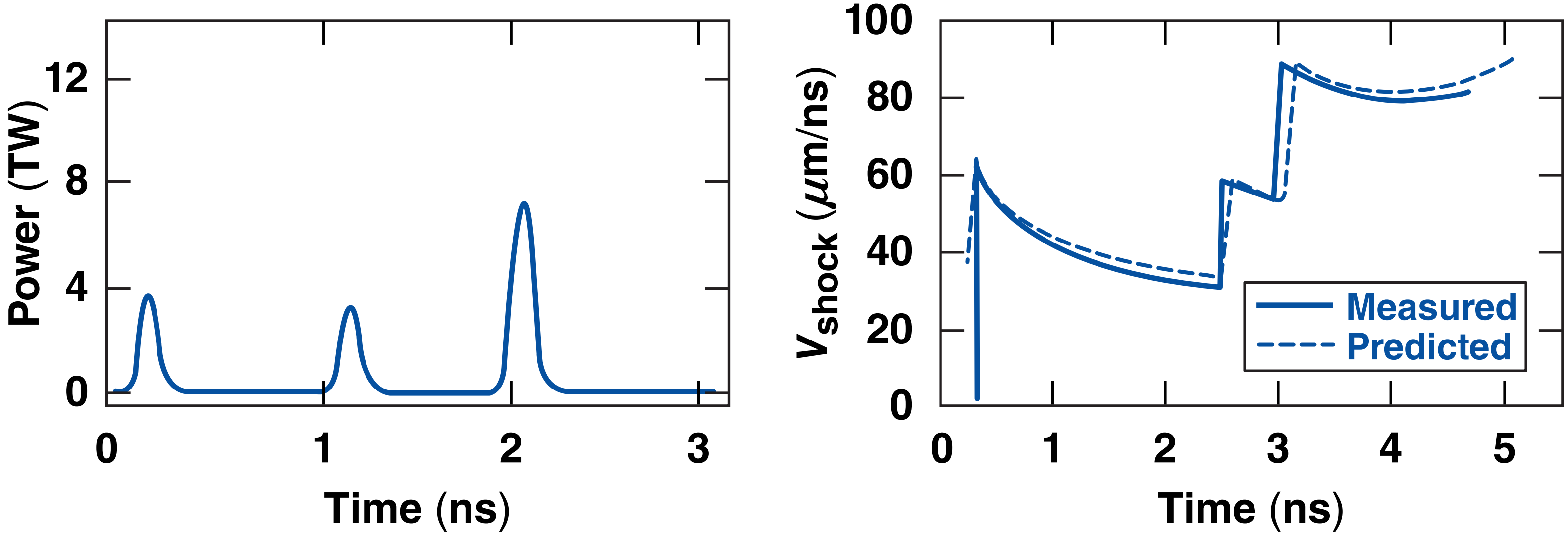
Velocity Interferometry System for Any Reflector (VISAR)



[1] T. R. Boehly (NO5.00009).
[2] T. R. Boehly *et al.*, Phys. Plasmas 16, 056302 (2009).

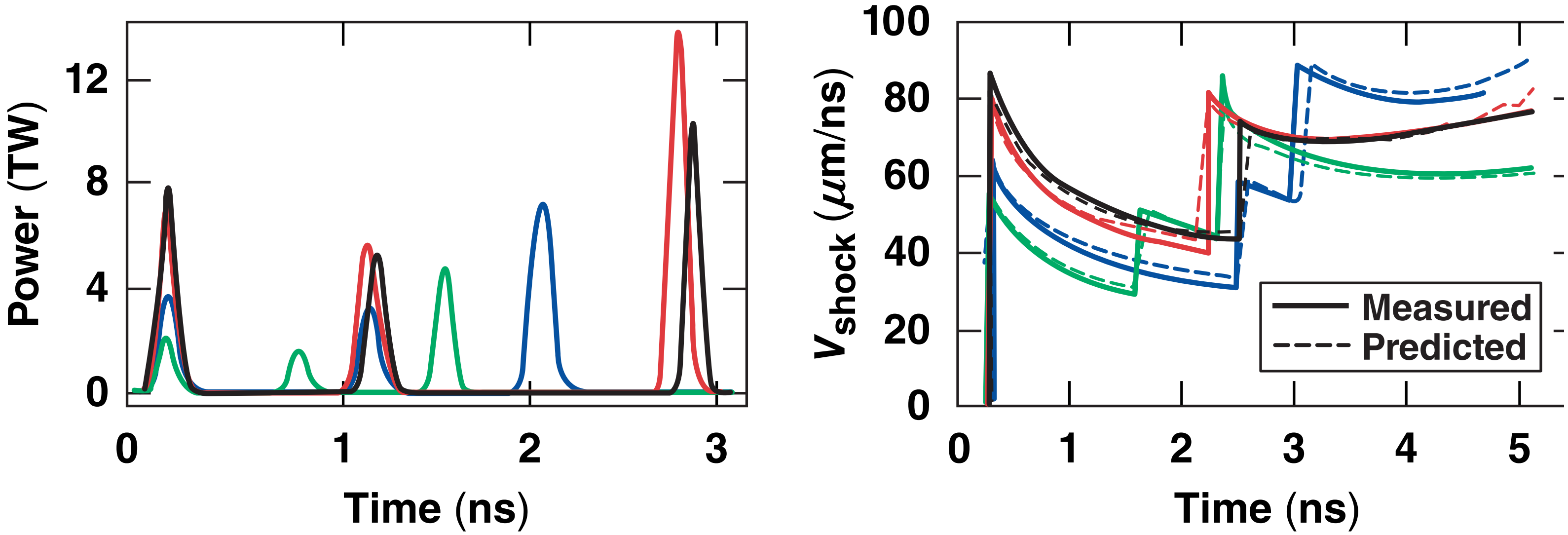
Simulations reproduce shock-velocity data very well for a variety of picket energies and picket timings

OMEGA direct drive



TC9015

Simulations reproduce shock-velocity data very well for a variety of picket energies and picket timings



Accuracy in shock-velocity prediction meets the ignition requirement.

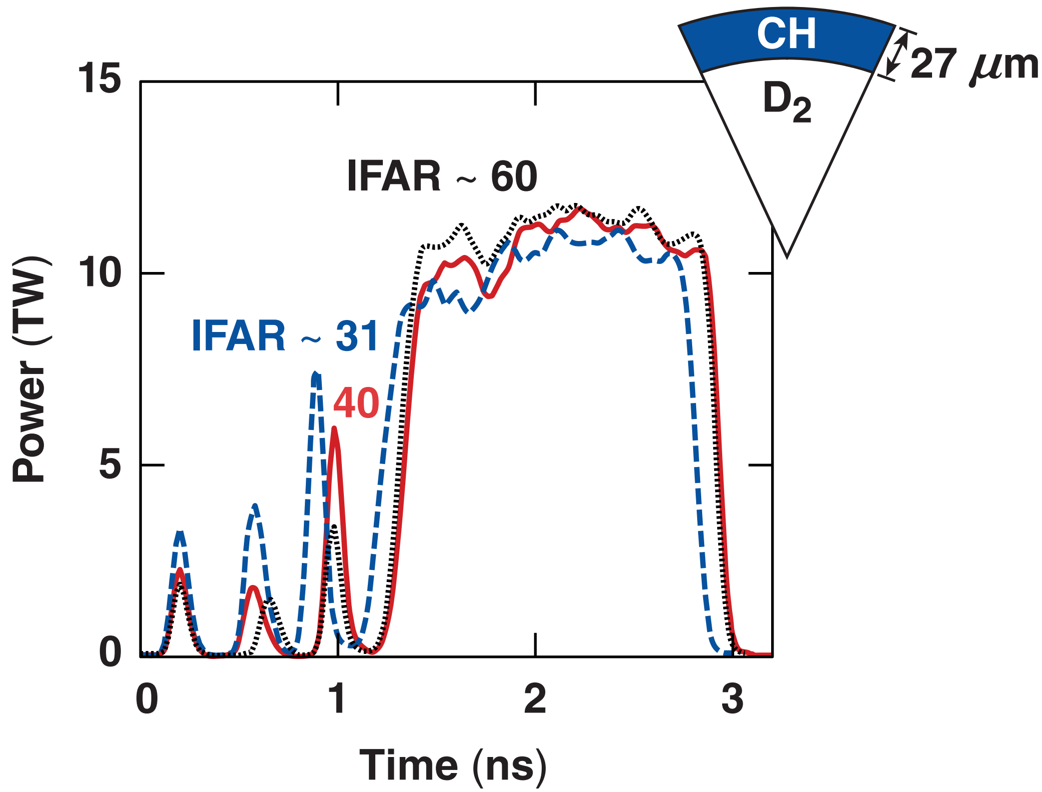
TC9016

Outline

- Ignition design and ignition conditions
- **Modeling areal density**
  - shock tuning
  - **control of short-wavelength perturbation growth**
- Hot-spot ion temperature and yield
  - validation of drive efficiency
  - effect of perturbation growth

The areal density is degraded for shells with excessive short-scale perturbation growth

- Warm CH implosions[1]
- In-flight aspect ratio (IFAR = radius/shell thickness) and adiabat are varied by changing picket energies

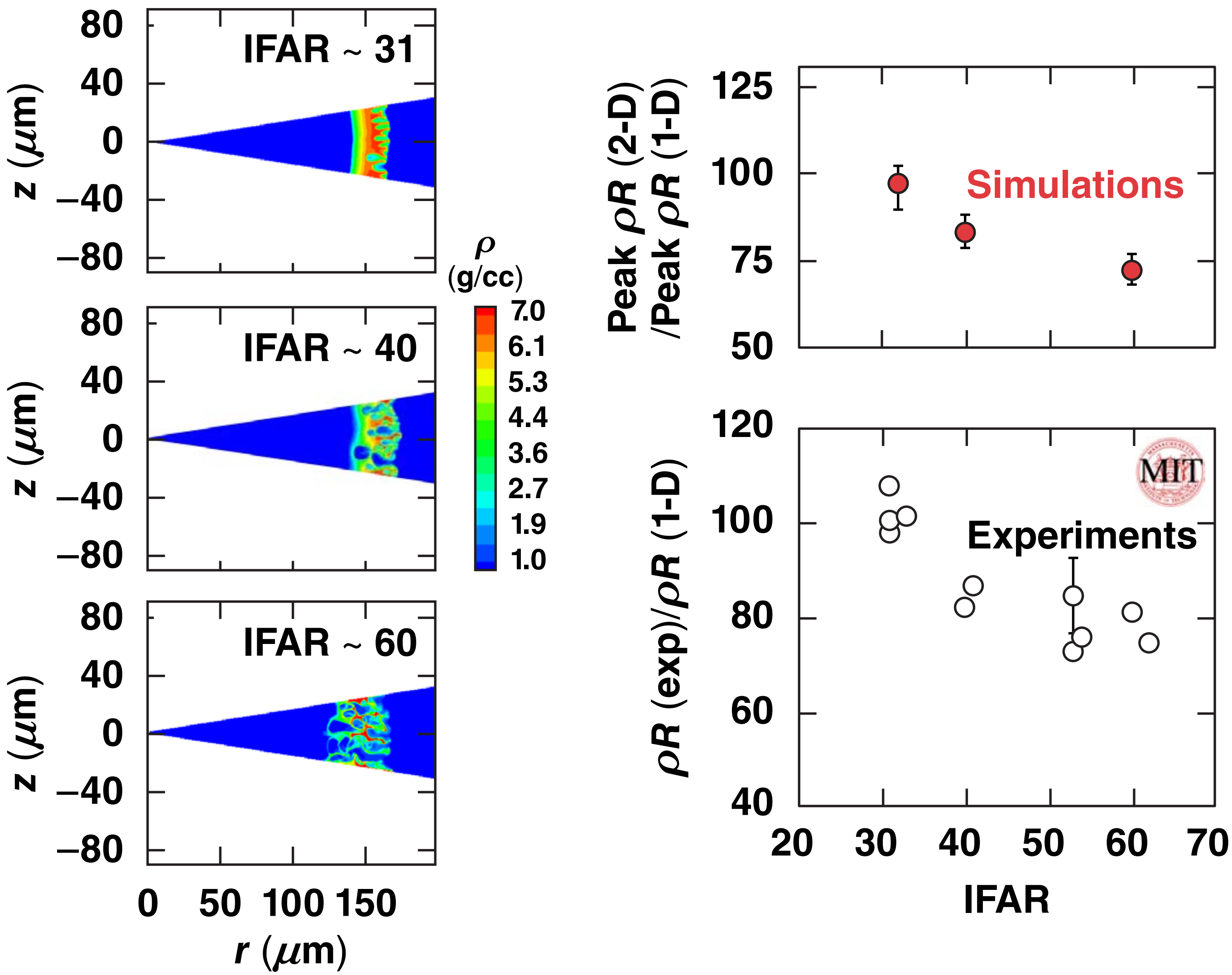


[1]P.B. Radha *et al.*, "Triple-Picket Warm Plastic–Shell Implosions on OMEGA" submitted to Phys. Plasmas.
[2]P. B. Radha (To5.00003).

TC9017

The areal density is degraded for shells with excessive short-scale perturbation growth

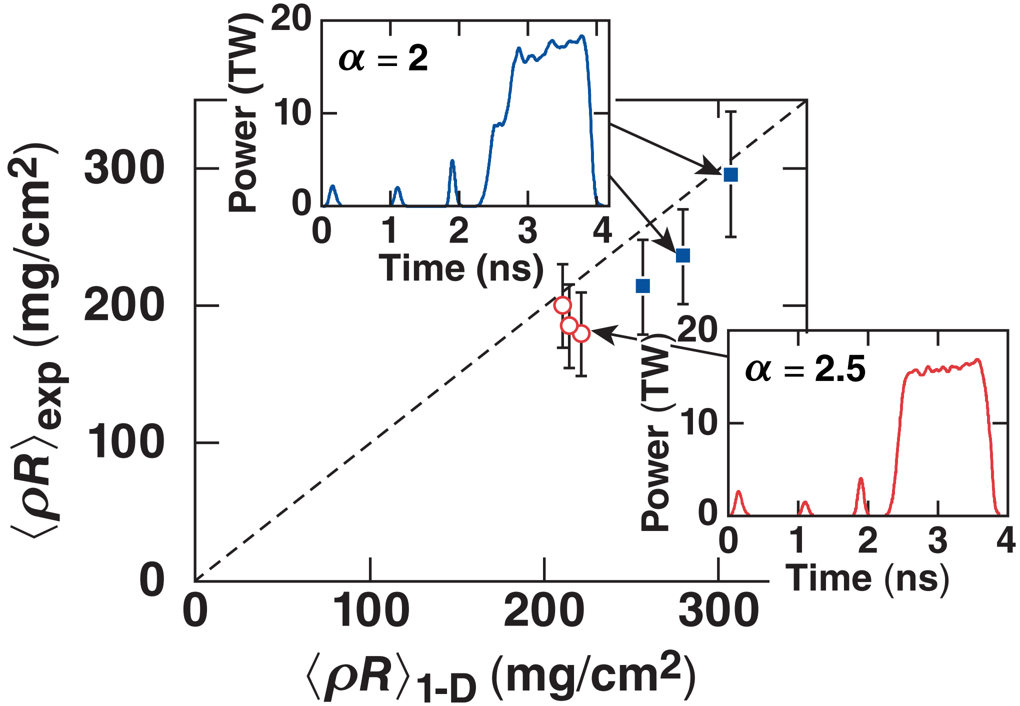
2-D *DRACO* imprint simulations

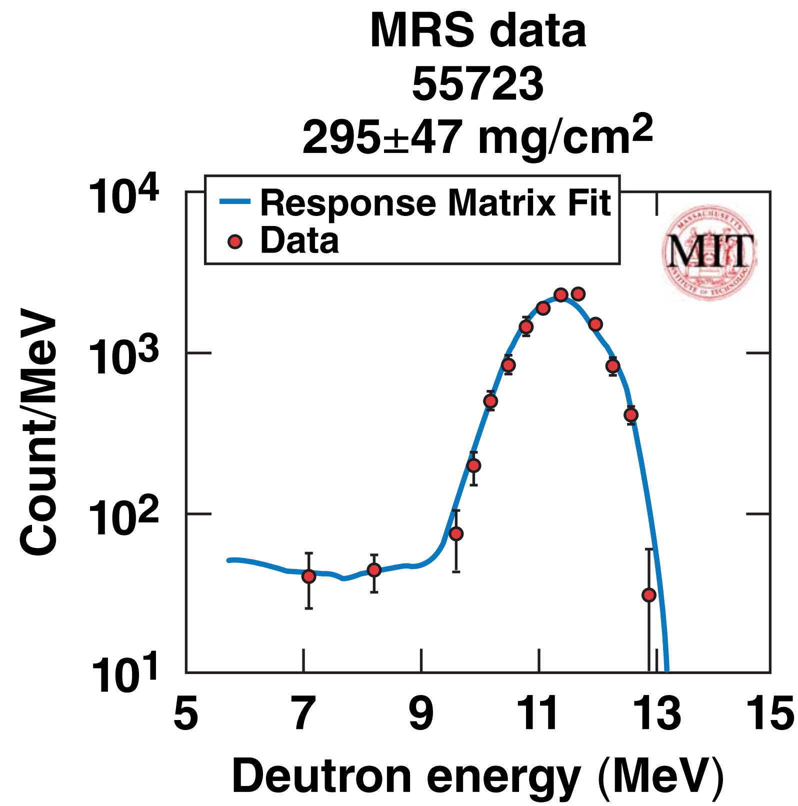


TC9018

The measured areal density in triple-picket cryogenic implosions is larger than 88% of the 1-D predicted value[1]

- Cryogenic implosions, IFAR ~ 30





The areal-density measurements confirm accuracy of shock tuning and shell stability to short-wavelength perturbations.

TC8896c

[1]V. N. Goncharov *et al*., Phys. Rev. Lett., 104, 165001 (2010).

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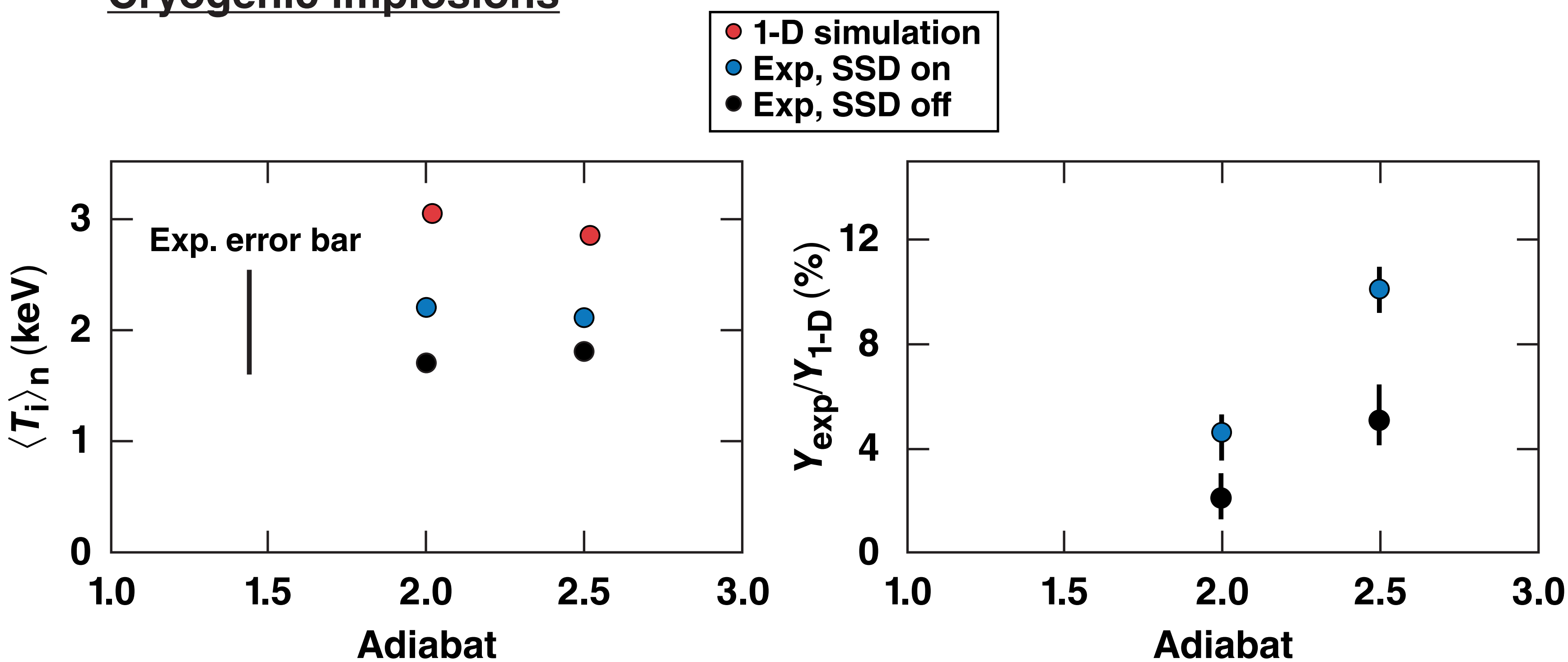
The measured ion temperature is ~25% lower than the 1-D predicted value

Cryogenic implosions

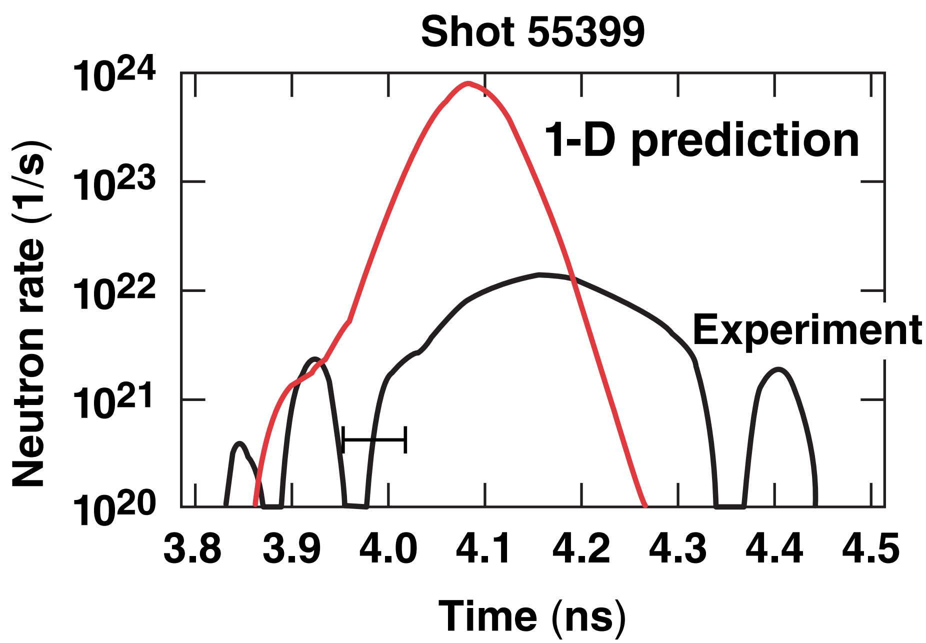


Neutron yield and temperature degradation are due to 3-D asymmetry effects or a reduction in hydrodynamic efficiency.

Bang time is an accurate measurement of shell velocity

UR LLE

Neutron-averaged ion temperature* $\langle T_i \rangle \sim V_{imp}^{1.25}$



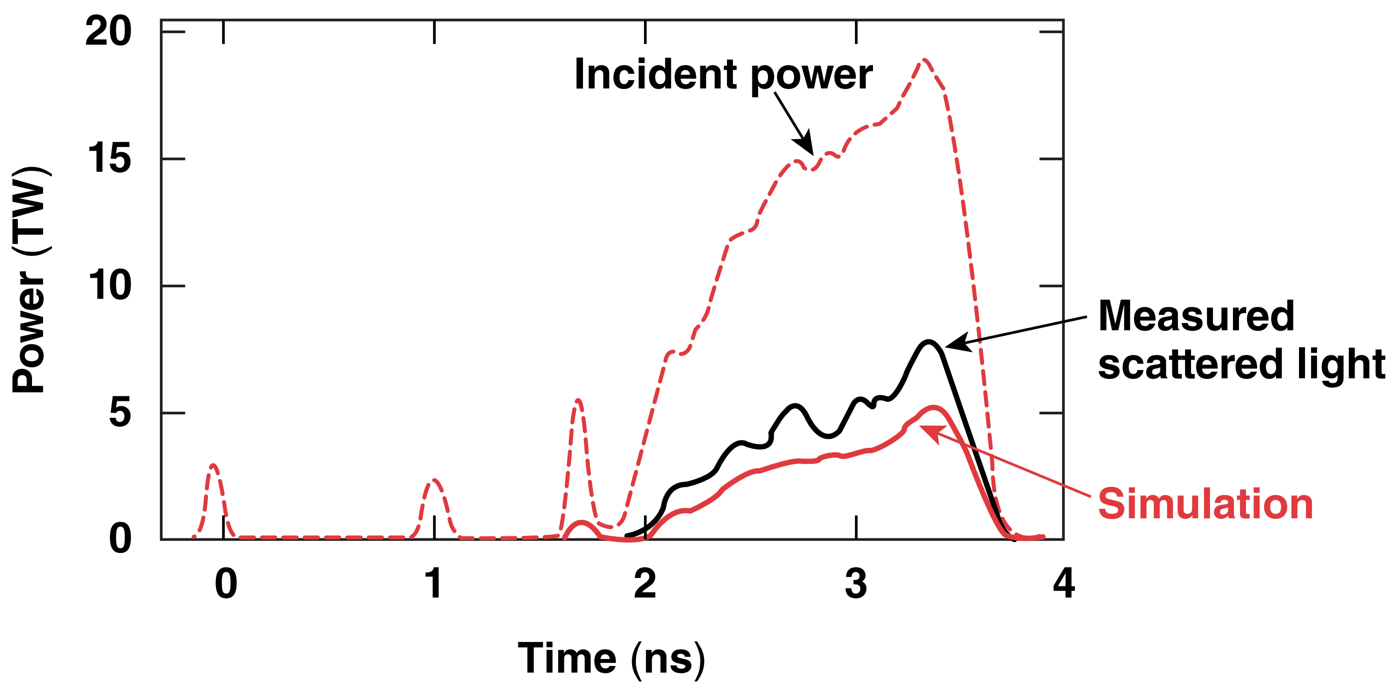
- Experimental bang time is delayed by ~80 ps

- $$\frac{\delta V_{imp}}{V_{imp}} = \frac{\delta t_{bang}}{t_{drive}} = \frac{80\ \text{ps}}{1300\ \text{ps}} = 6\%$$

	Simulated	Consistent with Bang Time
V_{imp}	3.0×10^7 cm/s	2.8×10^7 cm/s
$\langle T_i \rangle$	3.0 keV	2.8 keV

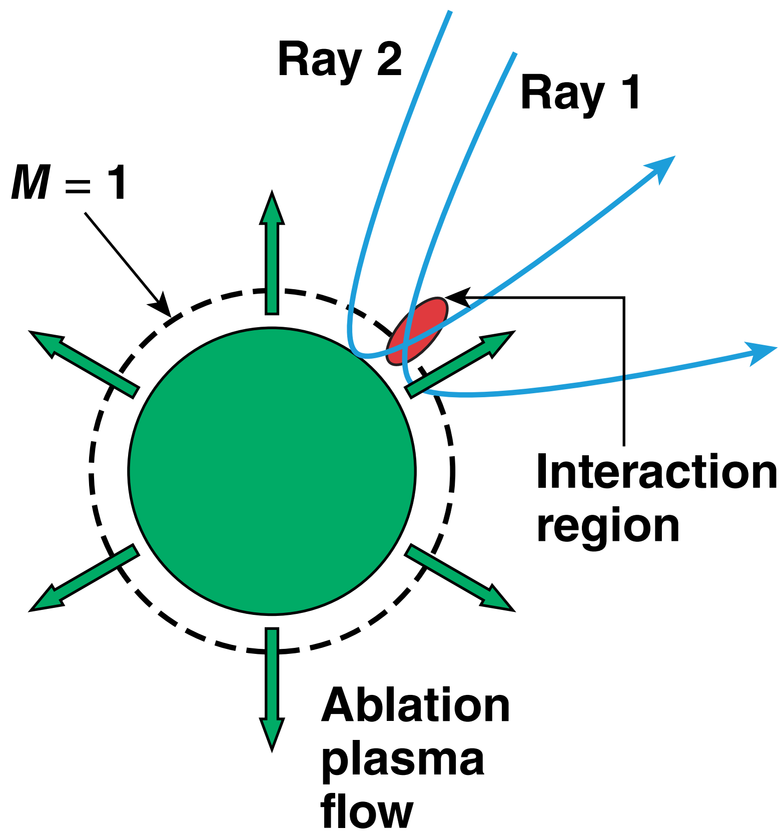
*C. D. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

The scattered-light measurement indicates a loss in laser coupling



Beam-to-beam energy transfer leads to a reduction in laser coupling[1]

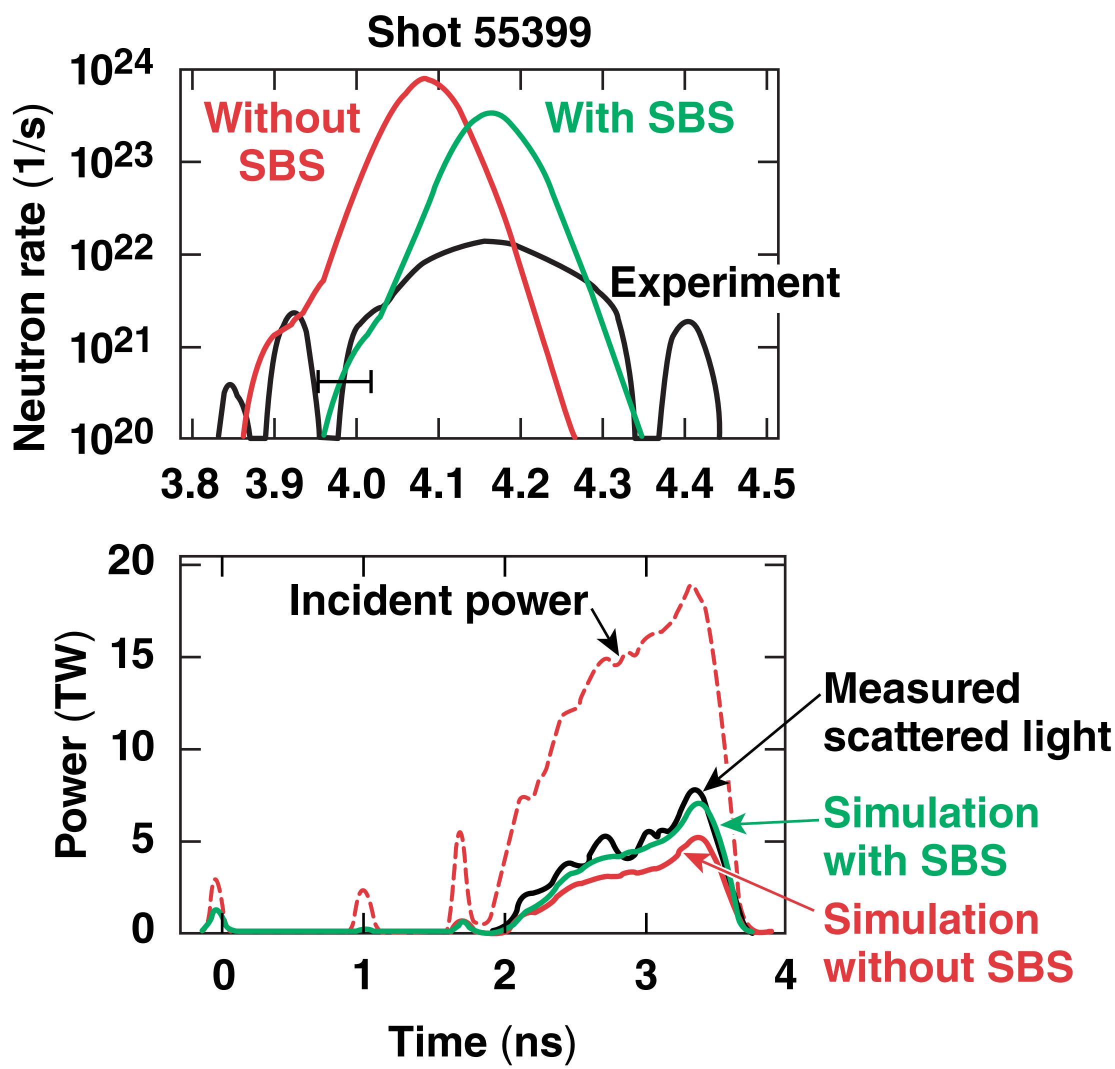
The transfer of energy from (1) to (2) is due to SBS before deposition[2]



[1] I. Igumenshchev *et al*., "Crossed-Beam Energy Transfer in ICF Implosions on OMEGA," submitted to Phys. Plasmas
[2] C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).

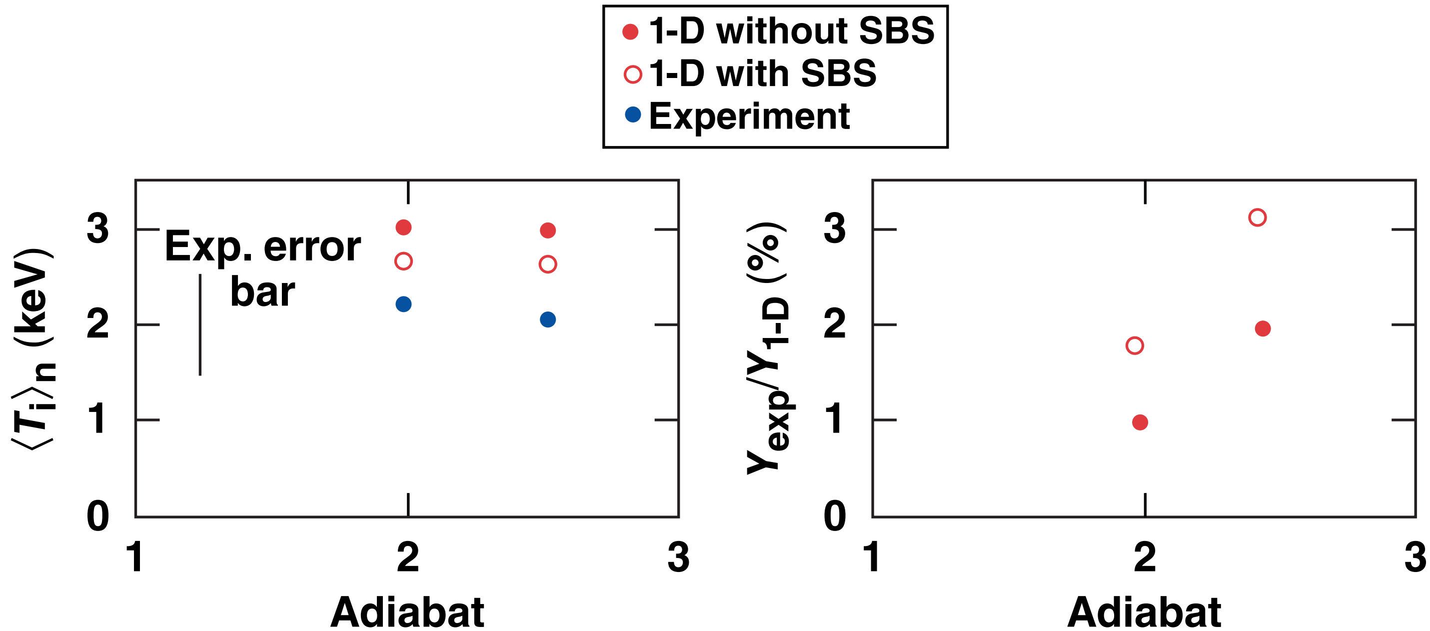
TC8901a

When beam-to-beam energy transfer is included, both the bang time and laser absorption are in good agreement with simulations



TC9022

Beam-to-beam energy transfer leads to a reduction in the T_i and yield predictions



An additional reduction in T_i and yield is caused by 3-D asymmetry effects.

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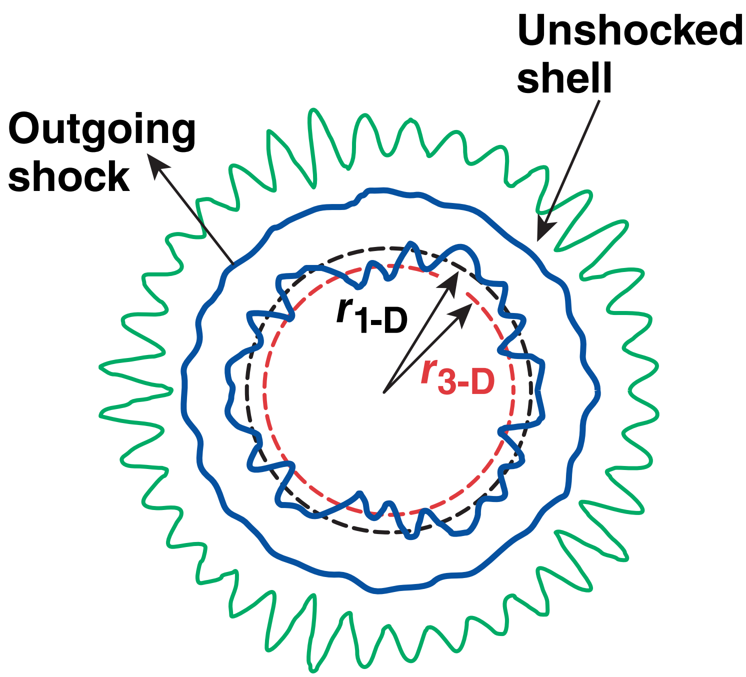
Perturbation growth leads to a reduction in "clean" hot-spot volume and ion temperature

Shell at deceleration phase



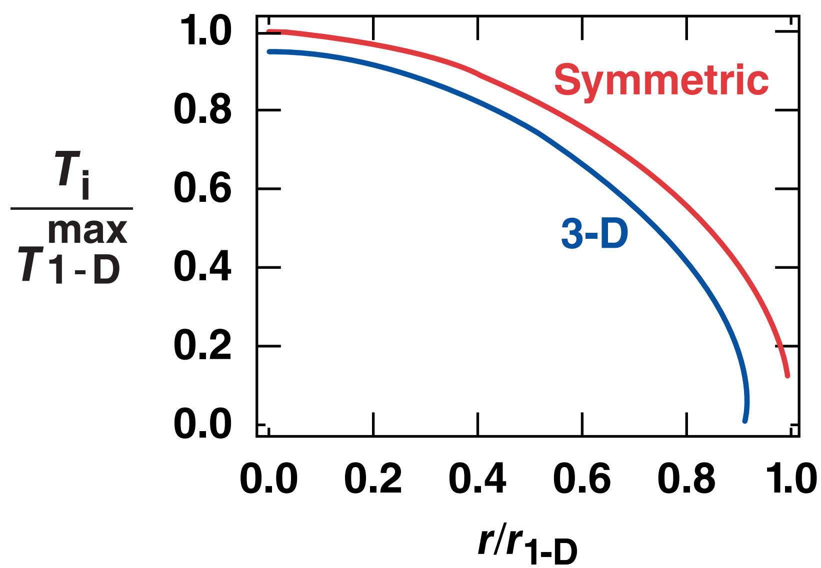
Effect of perturbations

(1) $V_{3\text{-D}} = \frac{4\pi}{3} r_{3\text{-D}}^3 < V_{1\text{-D}} = \frac{4\pi}{3} r_{1\text{-D}}^3$

$r_{3\text{-D}} = r_{1\text{-D}} - \sqrt{\sum_{\ell} (w_{\ell} a_{\ell})^2} = r_{1\text{-D}} (1 - \xi)$

Low–ℓ modes contribute less[1]

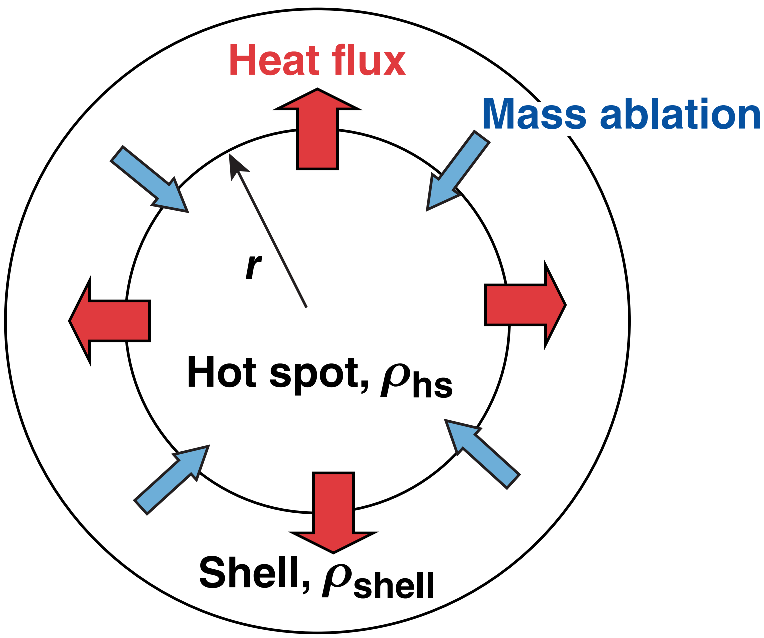
(2) Extra thermal conduction losses ⇒ lower T_e and T_i



[1]Kishony, Shvarts, Phys. Plasmas 8, 4925 (2001).

Ion-temperature reduction can be related to the hot-spot distortion fraction

Ref. 1: $PV \sim T^{5/2}\dfrac{T}{r} \Rightarrow V_a \sim \dfrac{T^{5/2}}{\rho_{shell} r}$



Perturbations move the shell mass closer to center. Ablation is more efficient. There is more mass in the hot spot, along with lower T_i.

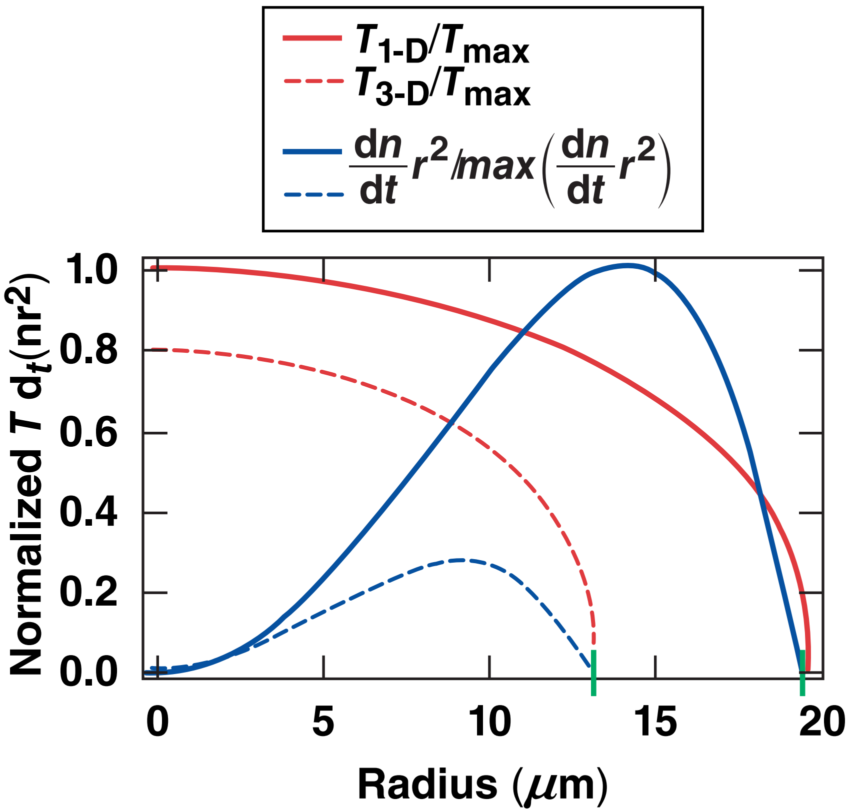
$$\frac{d}{dt}\left(\frac{4\pi}{3}\rho_{hs} r^3\right) = 4\pi r^2 \rho_{shell} V_a \sim r T_{hs}^{5/2}$$

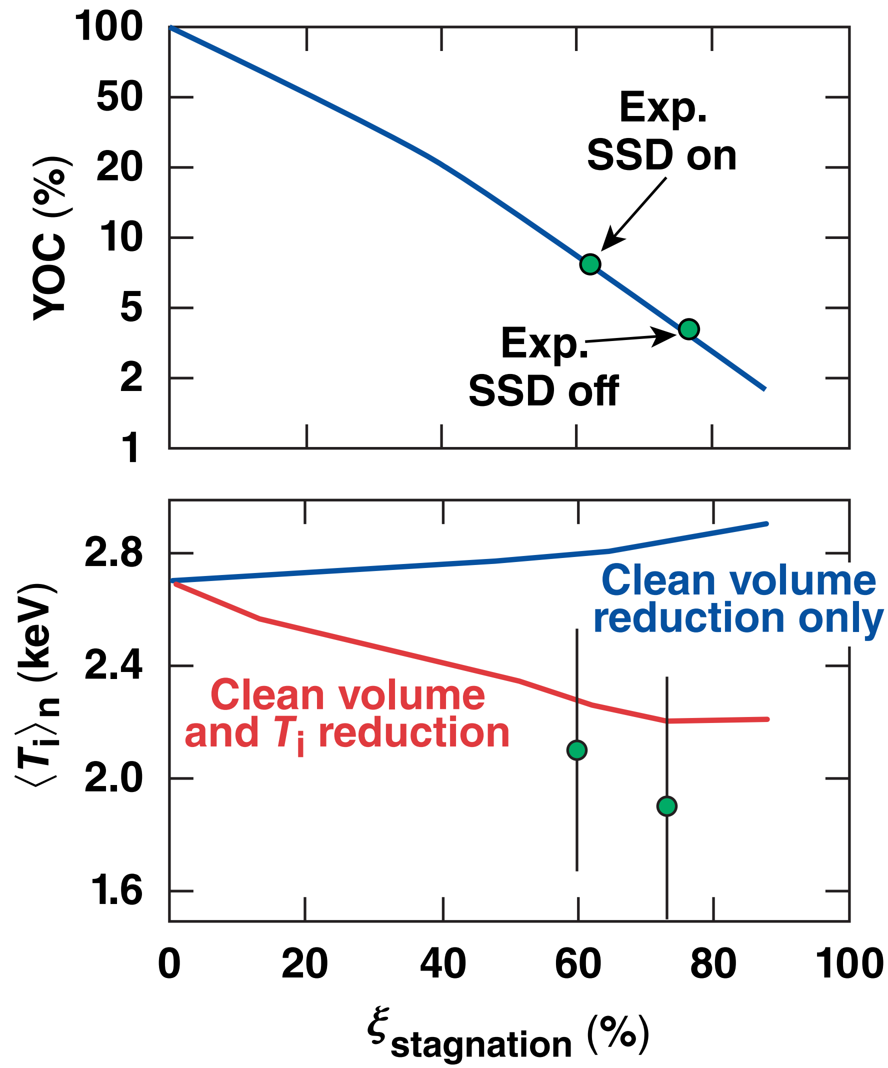
$$r_{3\text{-D}} = r_{1\text{-D}}(1-\xi),\ \ \rho_{hs} T_{hs} = \rho_{1\text{-D}} T_{1\text{-D}}$$

$$\boxed{(1-\xi)^2 \frac{d\rho_{hs}^{7/2}}{dt} + \frac{21}{2}\rho_{hs}^{7/2}(1-\xi)\frac{\dot{r}_{1\text{-D}}}{r_{1\text{-D}}} = \frac{d\rho_{1\text{-D}}^{7/2}}{dt} + \frac{21}{2}\rho_{1\text{-D}}^{7/2}\frac{\dot{r}_{1\text{-D}}}{r_{1\text{-D}}}}$$

[1] V. Lobatchev and R. Betti, *Phys. Rev. Lett.* 85, 4522 (2000).

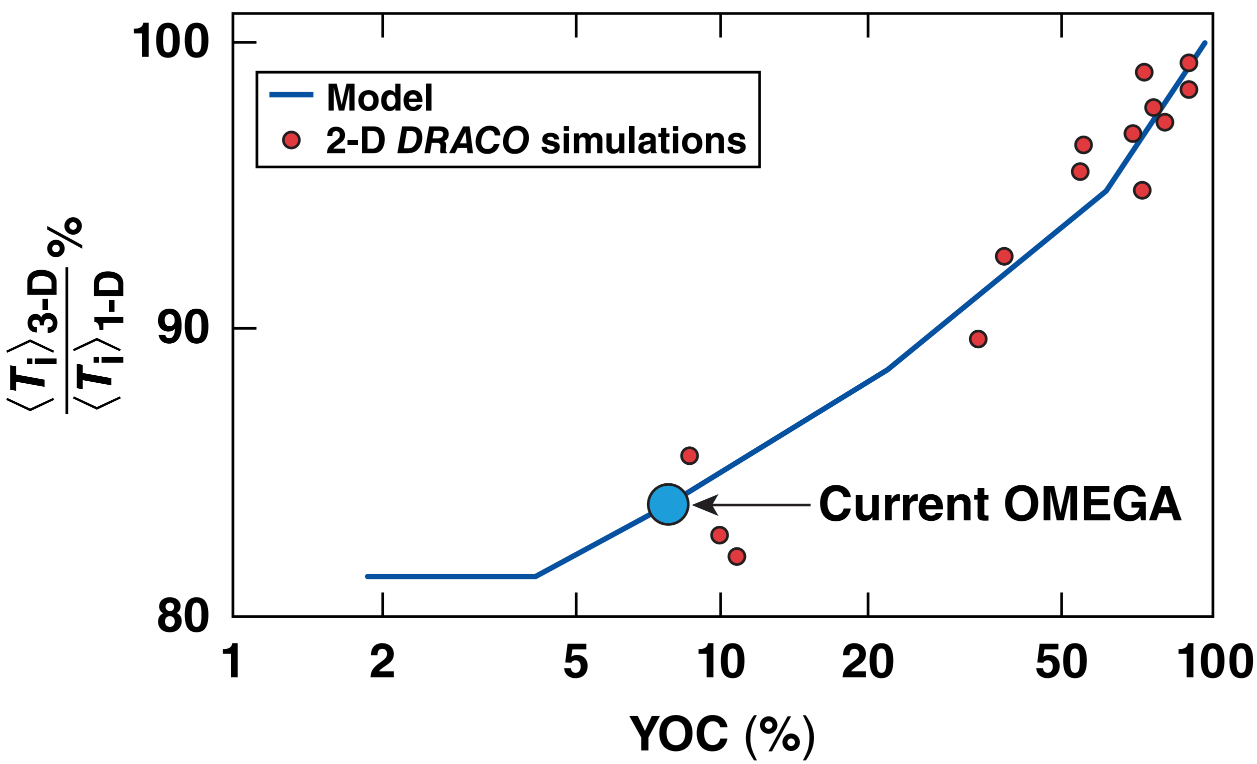
Model prediction for yield and T_i is consistent with the data





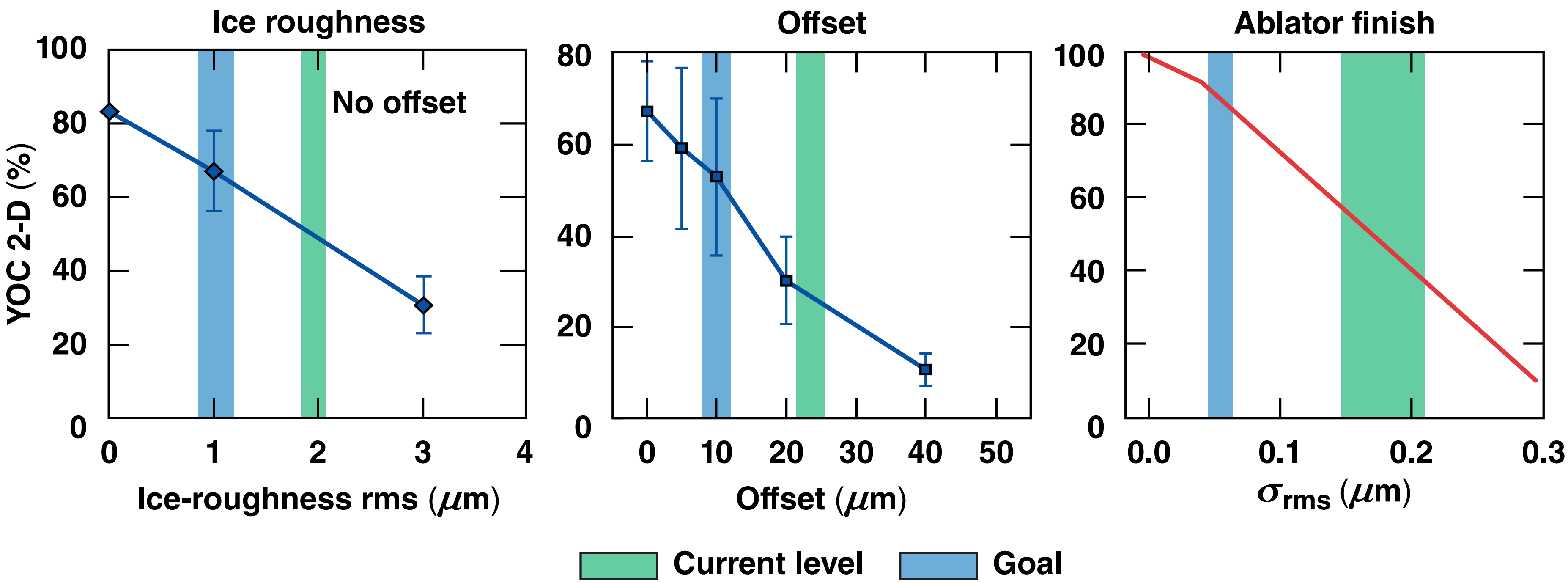
TC9026

2-D simulations confirm temperature reduction predicted by the model



Reducing target offset, ice roughness, and ablator finish is required to improve yield and T_i

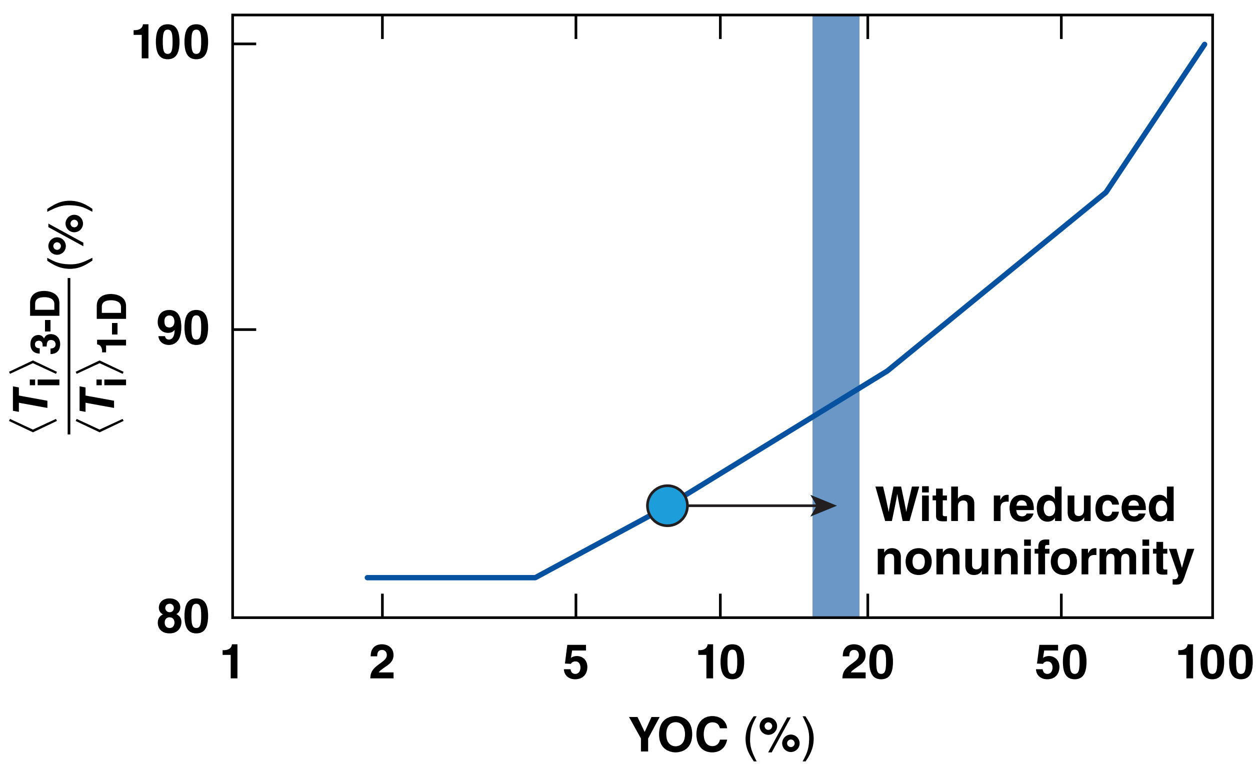
Results of 2-D *DRACO* Simulations[1]



TC9027

[1] S. X. Hu *et al*., Phys. Plasmas 17, 102706 (2010).

With nonuniformity sources meeting the goal, $\alpha = 2$ cryogenic implosions on OMEGA are predicted to achieve YOC ~15% to 20% with $\langle T_i \rangle_n \sim 2.4$ keV



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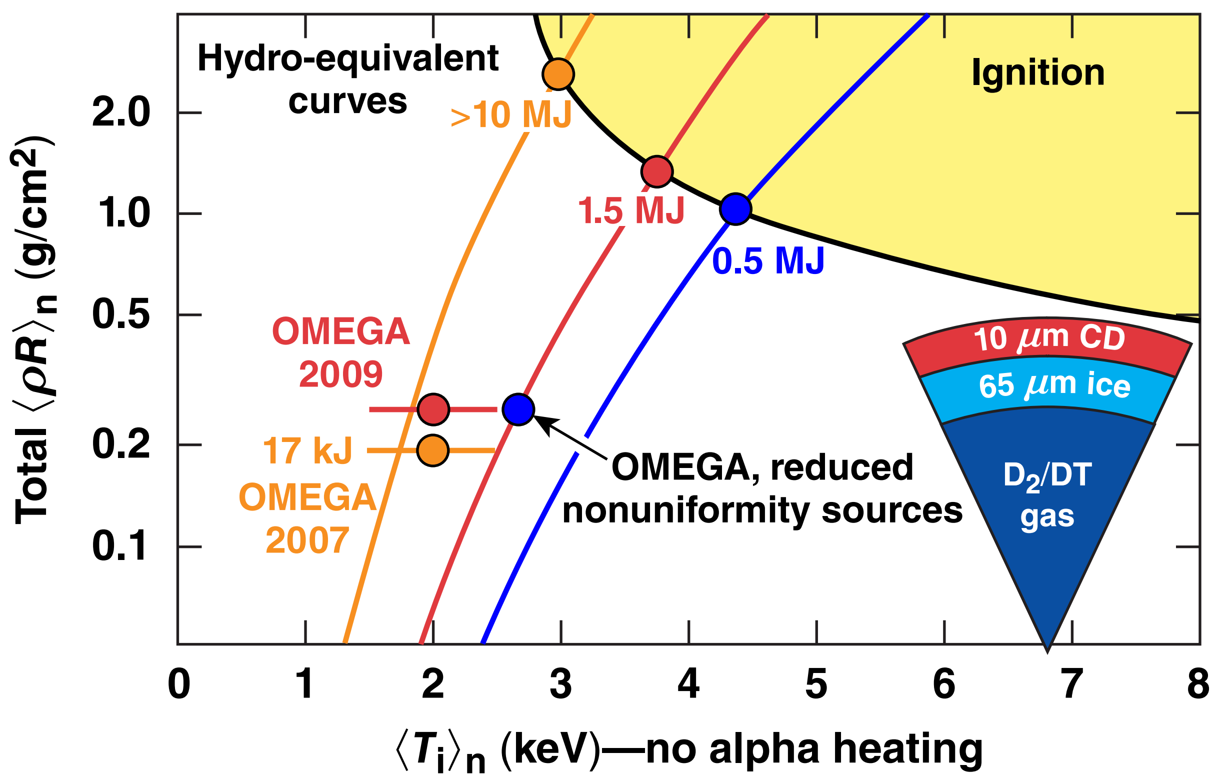

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