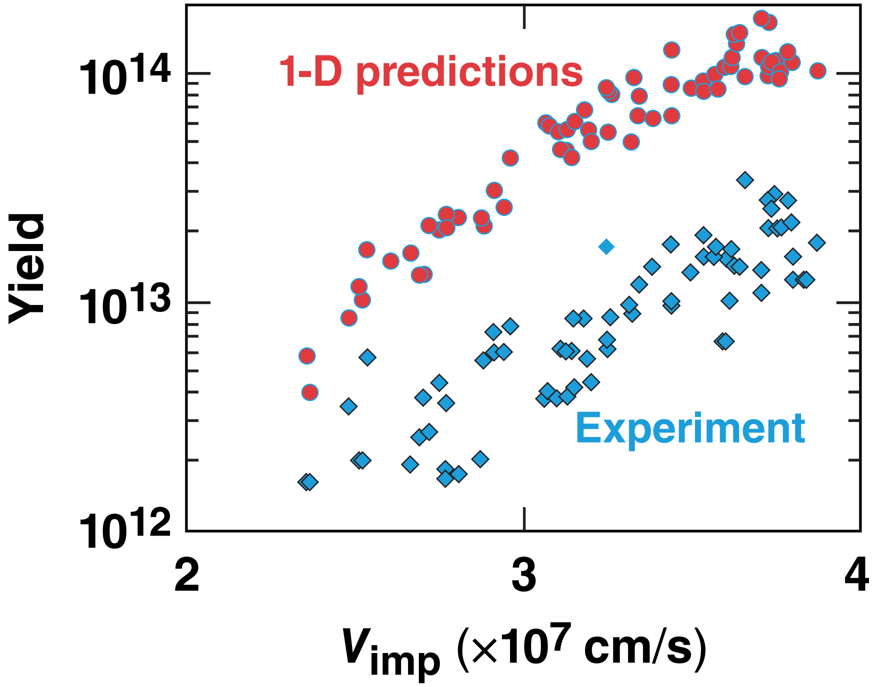
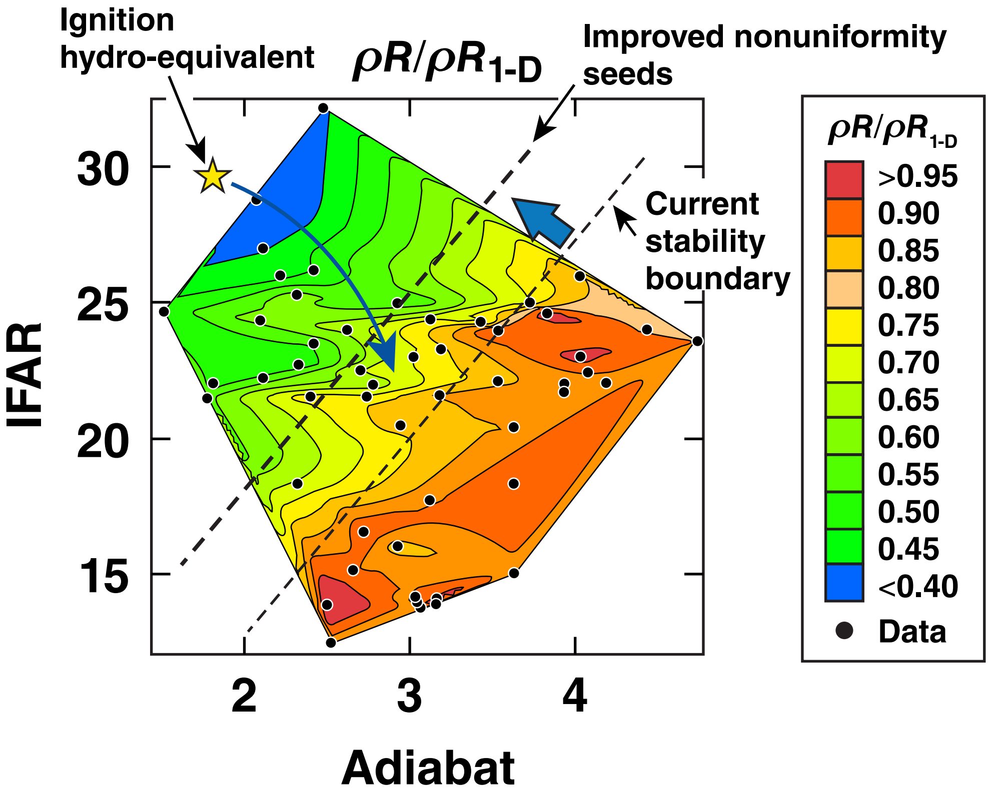
Demonstrating Ignition Hydrodynamic Equivalence in Cryogenic DT Implosions on OMEGA





V. N. Goncharov
University of Rochester
Laboratory for Laser Energetics

55th Annual Meeting of the American Physical Society Division of Plasma Physics
Denver, CO
11–15 November 2013

Summary

The perturbation degradation of OMEGA cryogenic implosions is understood in terms of unshocked shell mass at stagnation

- Yields in excess of 3.4 × 10^{13} [yield-over-clean (YOC) ~ 35%] and ion temperatures up to 4 keV were measured in cryogenic implosions with $V_{\text{imp}} \sim 3.8 \times 10^7$ cm/s
- Performance degradation in moderate-adiabat ($\alpha \sim 4$) implosions is fully understood by 2-D *DRACO* simulations
- Shells in lower-adiabat implosions ($\alpha \sim 2.5$) break up during acceleration, leading to an increased hot-spot mass and reduced convergence
- The unshocked mass at peak compression determines the impact of the ablator mix

Improving shell stability and mitigating cross-beam energy transfer (CBET) are required to demonstrate ignition hydrodynamic scaling on OMEGA.

Collaborators

T. C. Sangster, R. Betti, T. R. Boehly, T. J. B. Collins,
R. S. Craxton, J. A. Delettrez, D. H. Edgell, R. Epstein, C. J. Forrest,
D. H. Froula, V. Yu. Glebov, D. R. Harding, S. X. Hu,
I. V. Igumenshchev, R. Janezic, J. H. Kelly, T. J. Kessler, T. Z. Kosc,
S. J. Loucks, J. A. Marozas, F. J. Marshall, A. V. Maximov, R. L.
McCrory, P. W. McKenty, D. D. Meyerhofer, D. T. Michel,
J. F. Myatt, R. Nora, P. B. Radha, S. P. Regan, W. Seka, W. T. Shmayda,
R. W. Short, A. Shvydky, S. Skupsky, C. Sorce, C. Stoeckl,
and B. Yaakobi

Laboratory for Laser Energetics
University of Rochester

J. A. Frenje, M. Gatu Johnson, and R. D. Petrasso

Plasma Science and Fusion Center, MIT

D. T. Casey

Lawrence Livermore National Laboratory

Outline

- OMEGA cryogenic target design
- Target performance
- Performance analysis using 2-D *DRACO* simulations
- Performance degradation mechanisms
- Conclusions

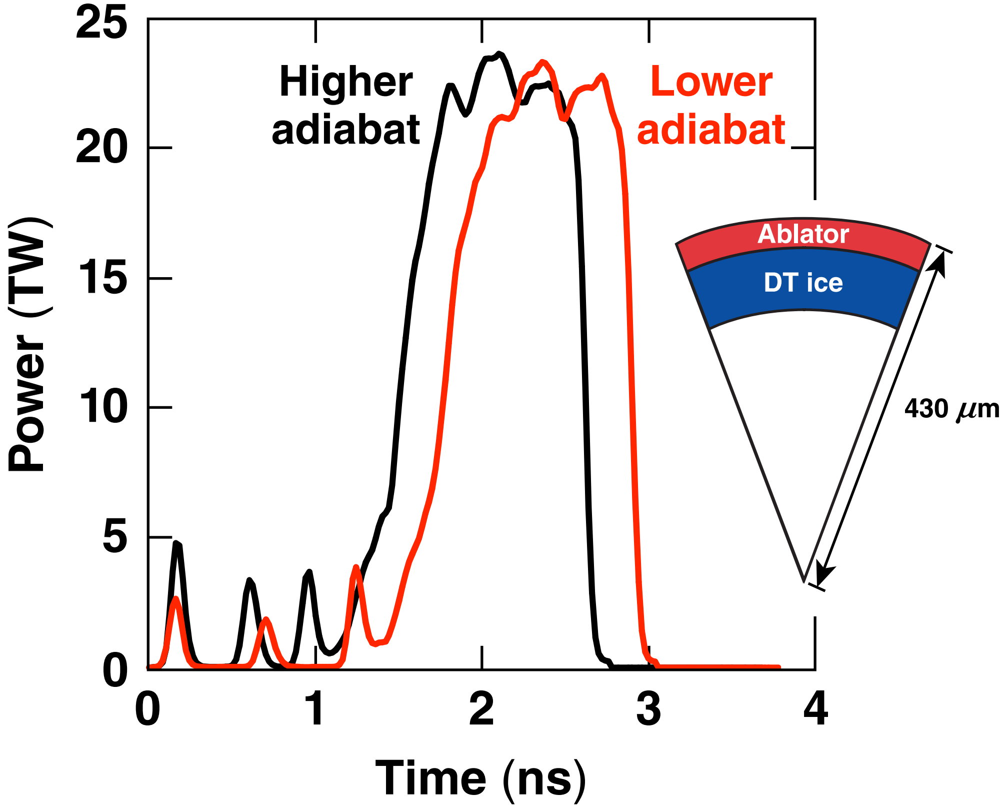
Direct-drive target performance is optimized by varying implosion velocity, in-flight aspect ratio (IFAR), fuel adiabat, and ablator material

- V_{imp} and IFAR are controlled by varying the ablator (7.5 to 12 μm) and fuel thickness (40 to 66 μm)

Adiabat
$\alpha = P/P_{Fermi}$

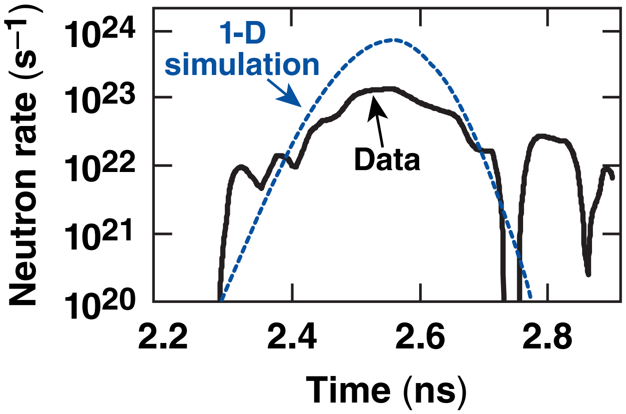
IFAR = shell radius/ shell thickness

Adiabat and IFAR are controlled by pulse shaping

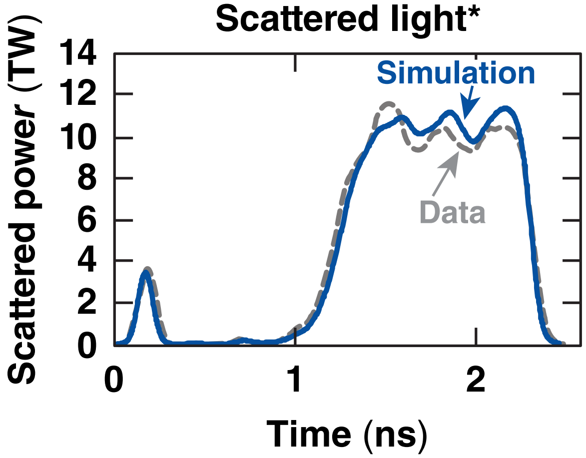


One-dimensional dynamics are verified using self-emission, bang time, and scattered-light measurements

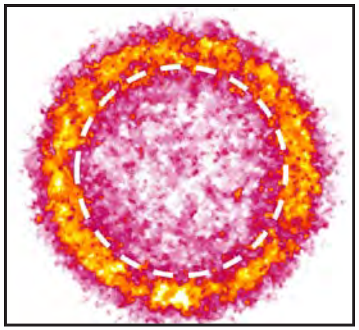
Neutron production

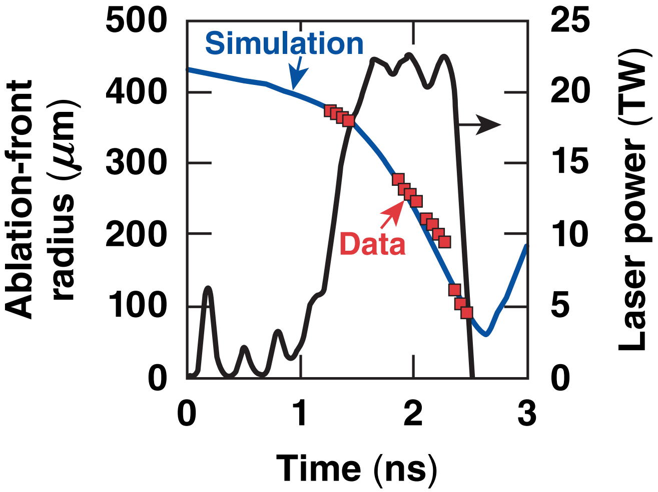


Scattered light*



Self-emission image**





---

[*] W. Seka *et al.*, Phys. Plasmas 15, 056312 (2008).

[**] D. T. Michel *et al.*, N07.00002, this conference.

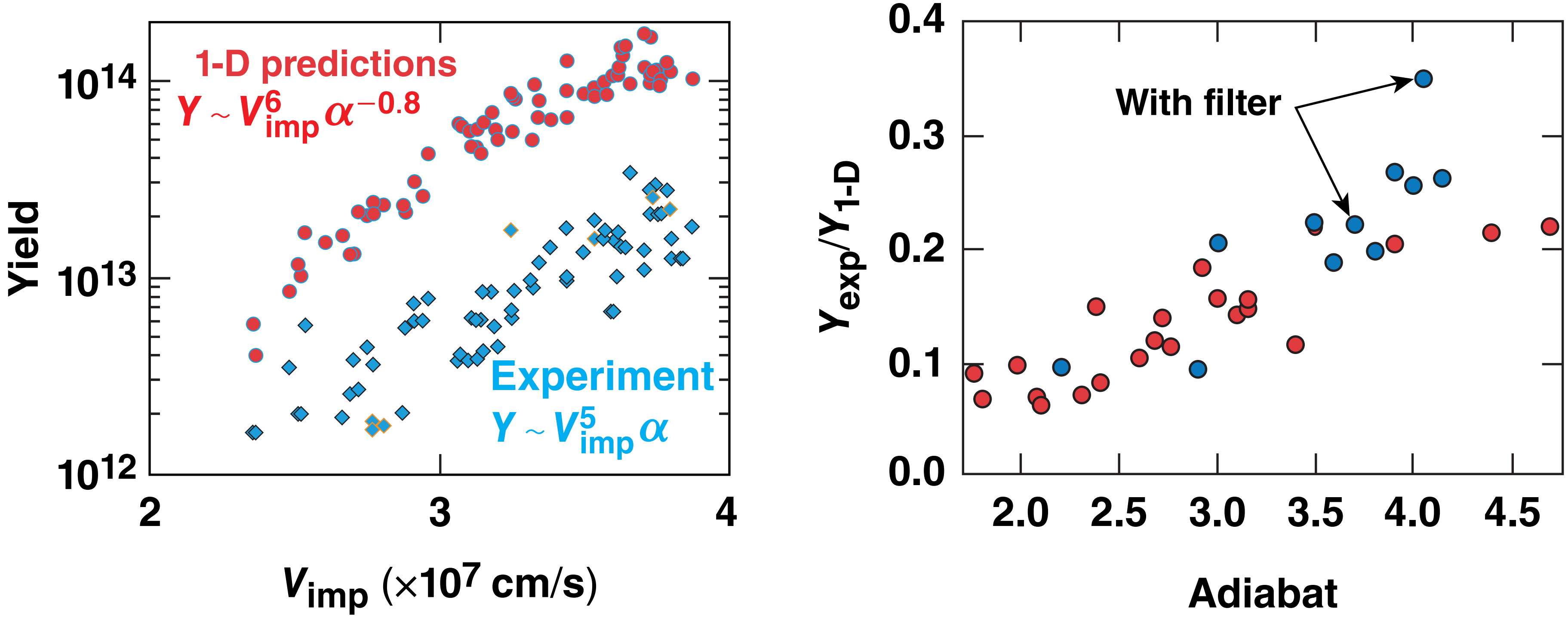
TC10789a

Outline

- OMEGA cryogenic target design
- **Target performance**
- Performance analysis using 2-D *DRACO* simulations
- Performance degradation mechanisms
- Conclusions

Target Performance

Target yield has a strong dependence on implosion velocity

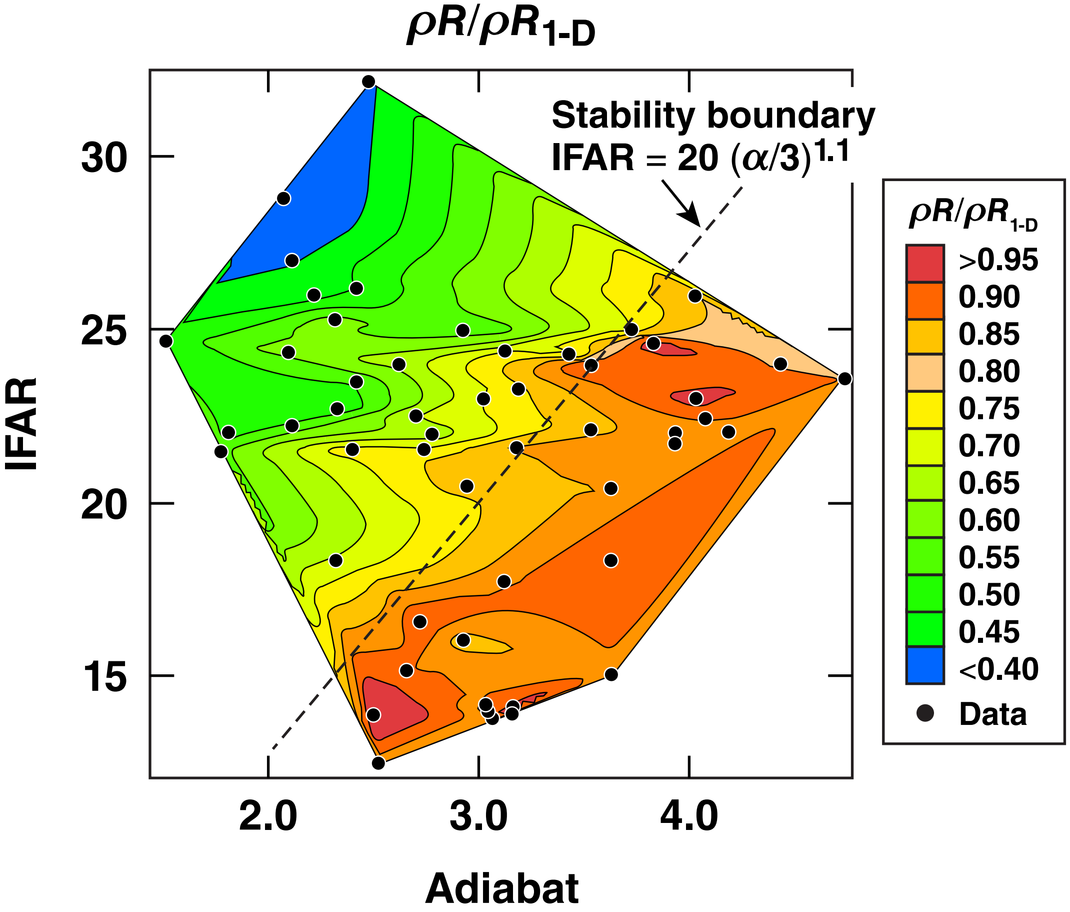


Yields for moderate-adiabat implosions increased by removing non-hydrogen fuel contaminants with a PdAg filter.

TC10812a

Target Performance

Fuel compression is degraded for low-adiabat, high-IFAR implosions



The maximum hot-spot pressure can be estimated using the measured neutron production rate

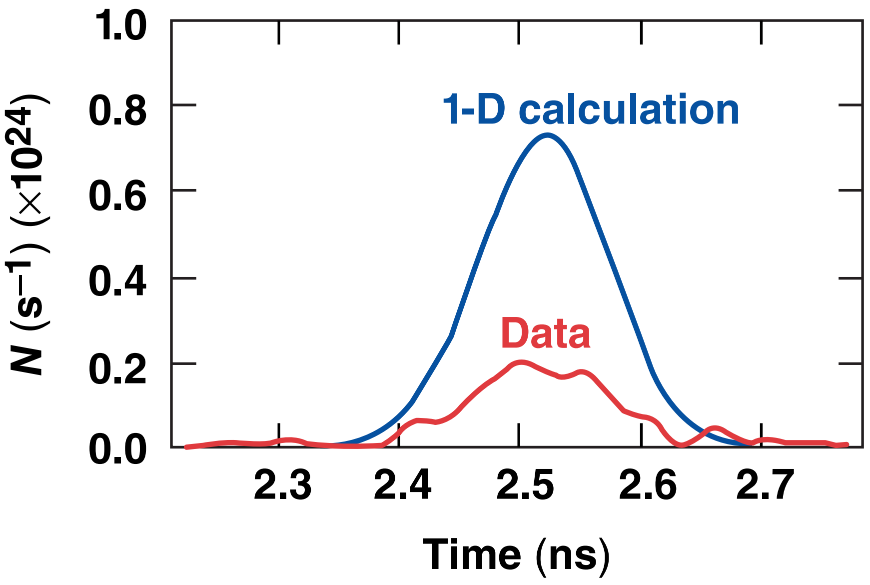
$$\frac{dN}{dt} \sim n^2 \langle \sigma v \rangle V_{hs} \sim p_{hs}^2 V_{hs} T^{2.5}$$

$$p_{hs} V_{hs}^{5/3} = \text{const}$$

$$\frac{dN}{dt} \sim p_{hs}^{7/5} T^{2.5}$$

Measured

$$p_{exp} \simeq p_{sim} \left(\frac{T_{exp}}{T_{sim}} \right)^{-1.8} \left(\frac{\dot{N}_{exp}}{\dot{N}_{sim}} \right)^{-0.7}$$

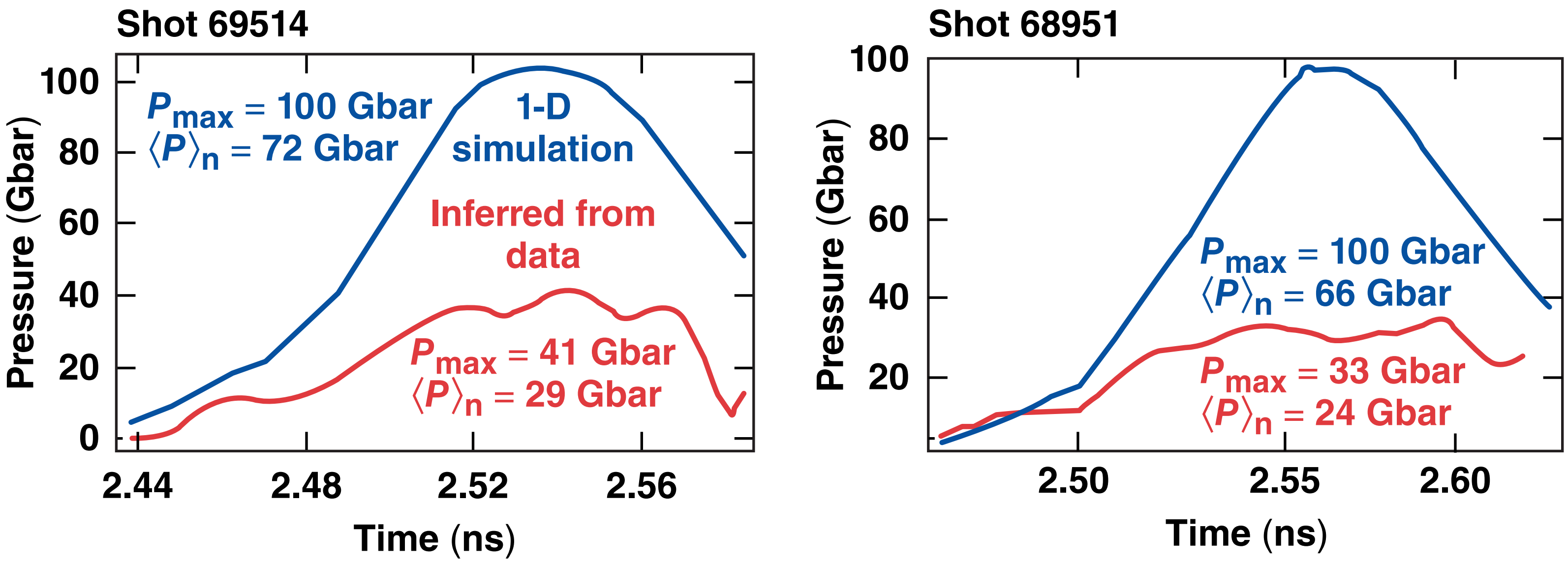


---

*For alternative calculations of P_{hs} see next talk by Nora *et al*., GI3.00002.

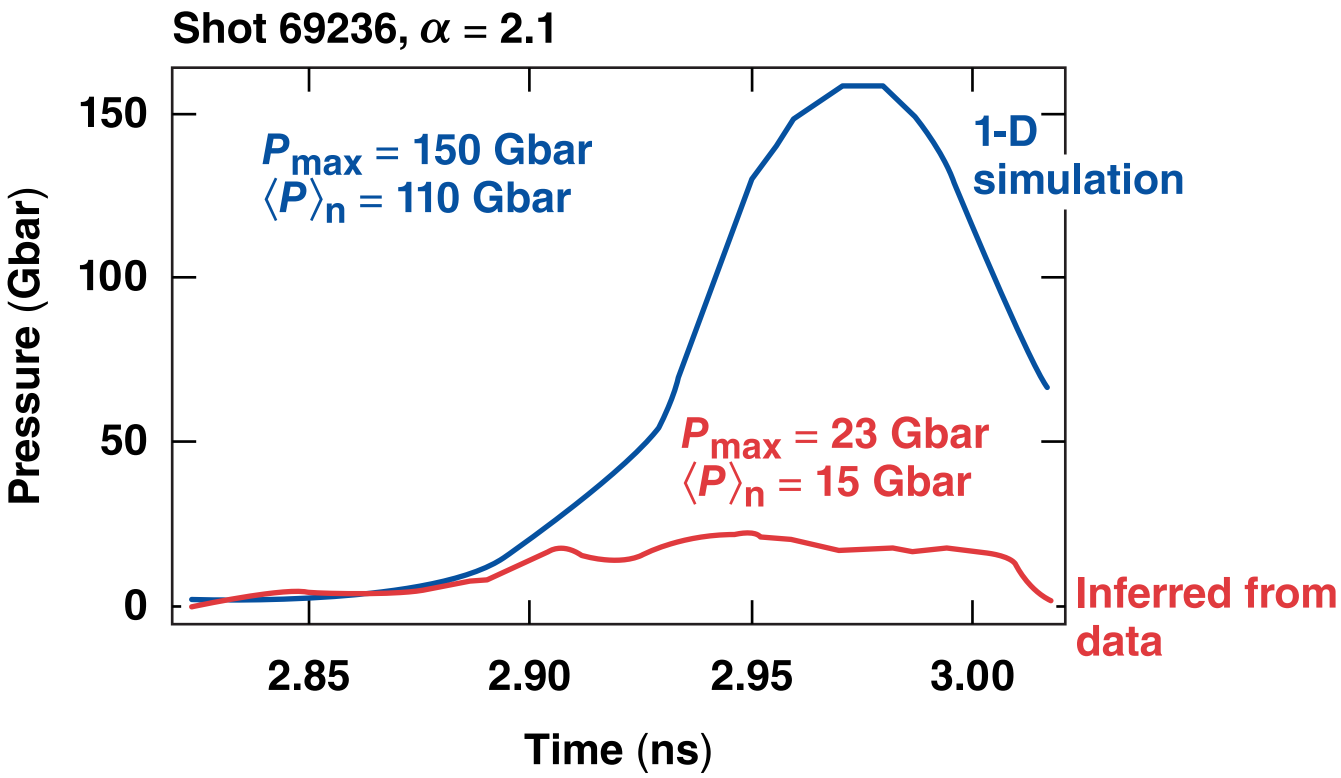
Pressures up to ~40 Gbar are inferred in $\alpha \sim 4$ implosions

Central pressure



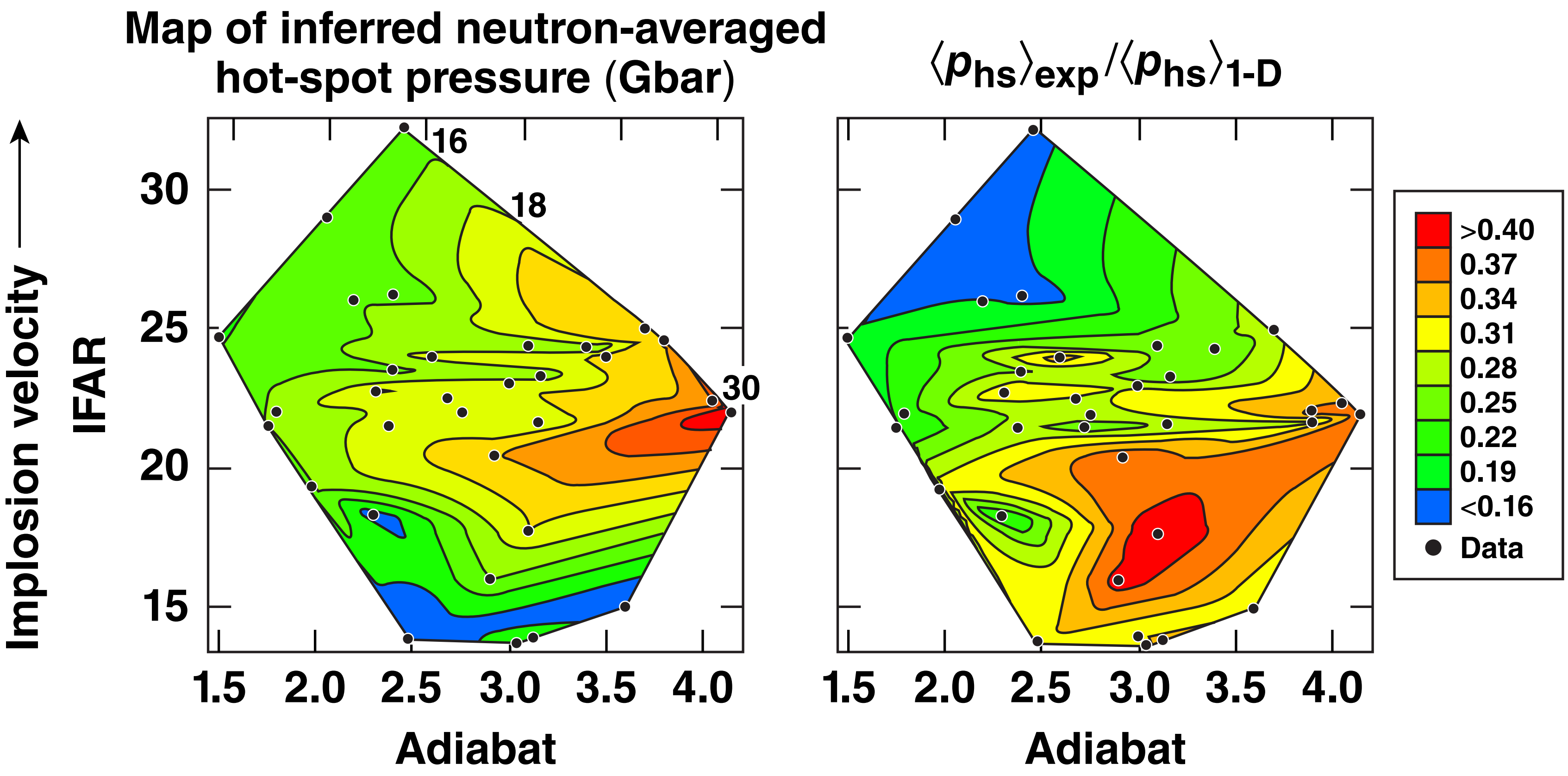
Target Performance

Pressure is significantly reduced in low-adiabat ($\alpha < 2.5$) implosions



TC10958

The highest hot-spot pressure is achieved for α ~ 4 implosions at IFAR ~ 22



Map of inferred neutron-averaged hot-spot pressure (Gbar)

$\langle p_{hs} \rangle_{exp} / \langle p_{hs} \rangle_{1\text{-}D}$

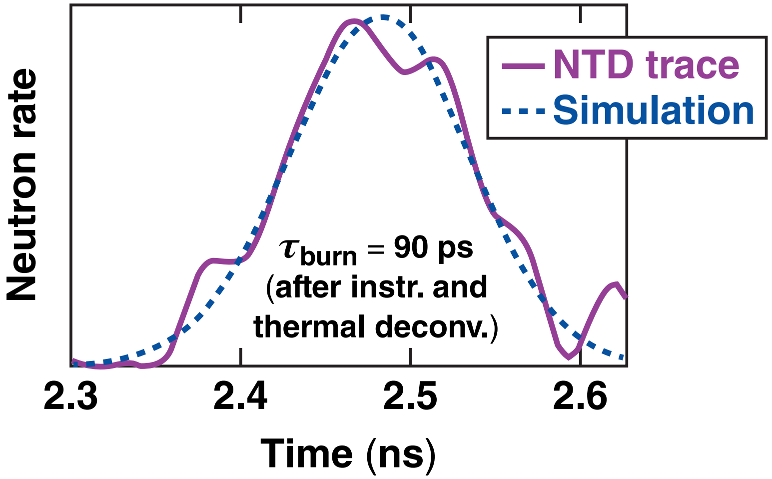
Outline

- OMEGA cryogenic target design
- Target performance
- **Performance analysis using 2-D *DRACO* simulations**
- Performance degradation mechanisms
- Conclusions

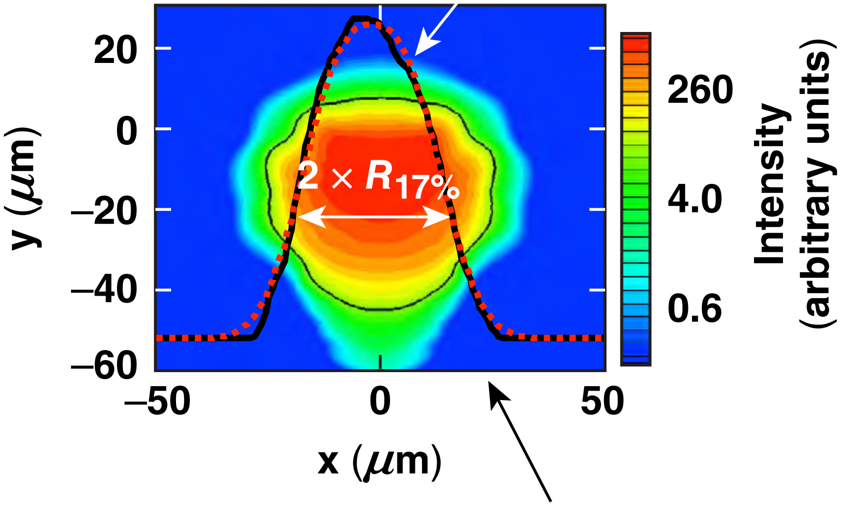
Two-dimensional simulations for $\alpha \gtrsim 4$ implosions reproduce measured stagnation quantities*

- Sources of nonuniformity included in simulation: laser imprint, ice roughness, power imbalance, and beam mistiming

Neutron temporal diagnostic (NTD) for shot 69514



Measured self-emission profile for shot 69514



*SPECT3D*** post-processed *DRACO* simulations

	Simulation	Experiment
Yield	3.9×10^{13}	3.0×10^{13}
T_i	3.7 keV	3.6 keV
ρR	0.18 g/cm^2	0.17 g/cm^2
R_{17}	24.4 μm	25.2 μm
P_{hs}	32 Gbar	30 Gbar

E22296f

---

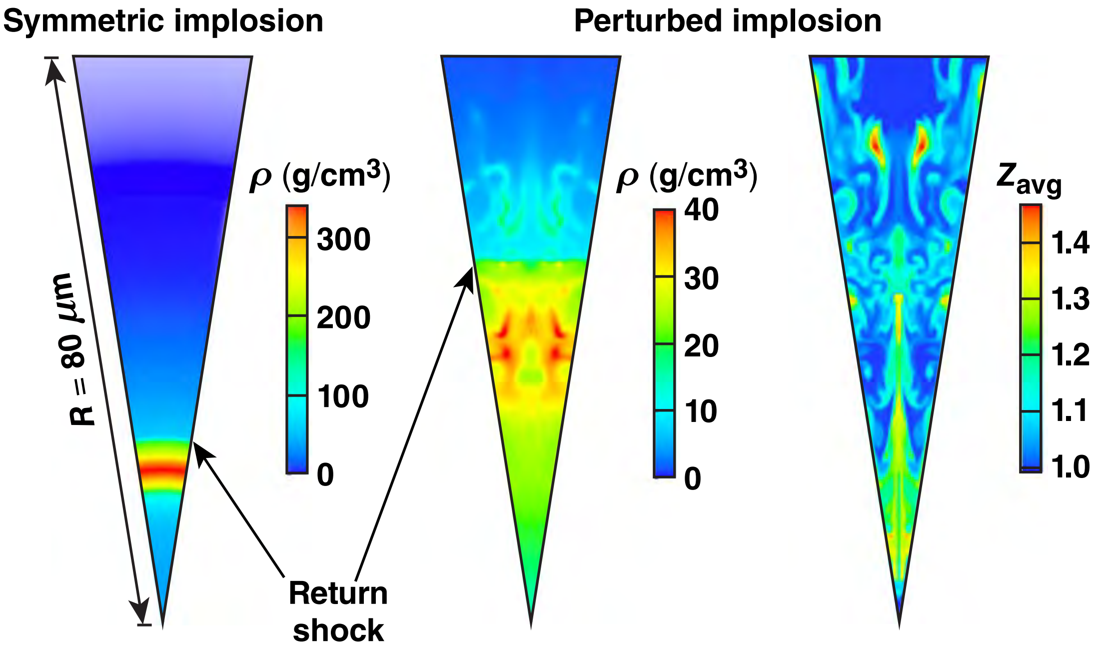
*S. X. Hu, UO4.00009, this conference.

**Prism Computational Sciences, Inc., Madison, WI, Report PCS-R-025, Ver. 2.1 (2001).

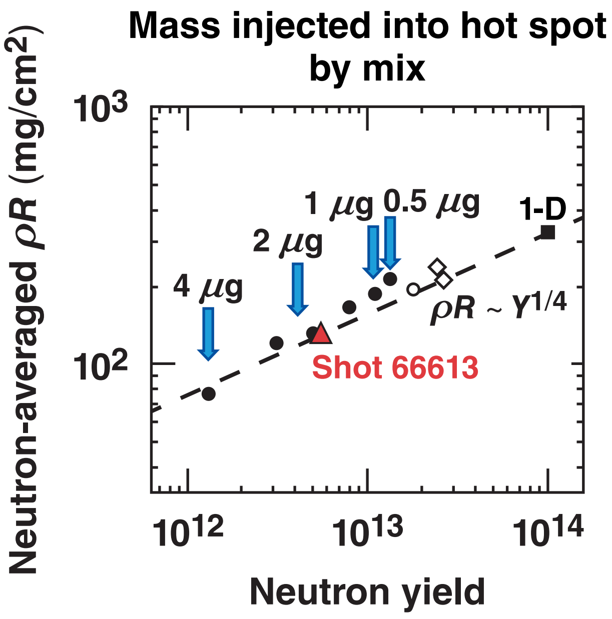
2-D Simulations

Shell instability is the main candidate for performance degradation in low-adiabat implosions

- Simulations* include ~100 surface features, size: 5 to 20 μm in diameter, 0.5 to 1.0 μm in depth


Symmetric implosion

Perturbed implosion


Mass injected into hot spot by mix

The main goal of these simulations is to identify a possible hydrodynamic scenario that explains the observations.

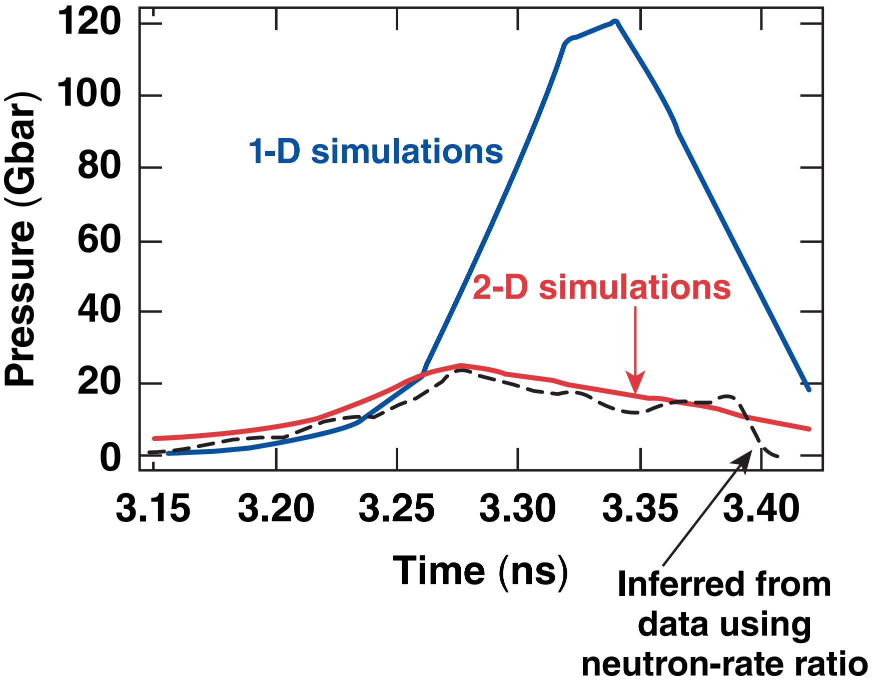
---

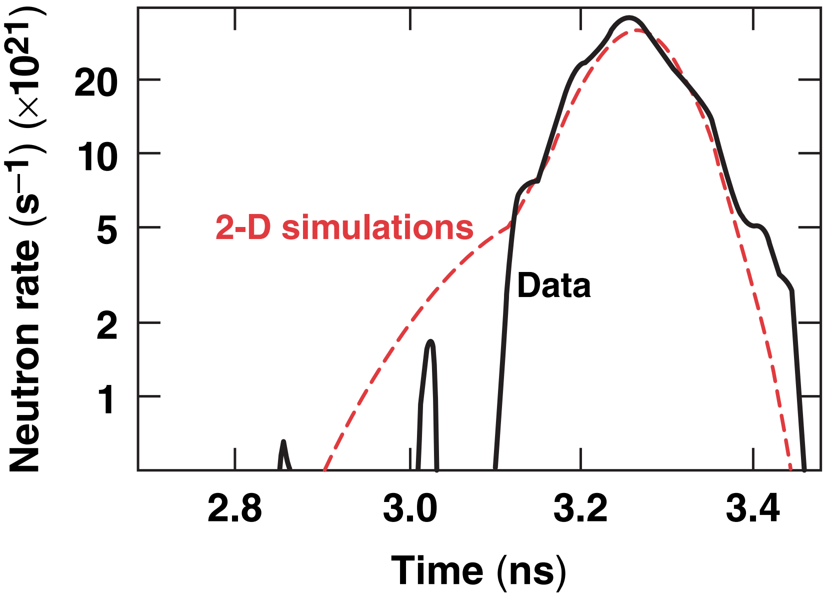
*I. V. Igumenshchev *et al.*, Phys. Plasmas 20, 082703 (2013).

2-D Simulations

Hydrodynamic simulations including local defects match the evolution of hot-spot pressure and neutron rate

Shot 66613, $\alpha = 2$

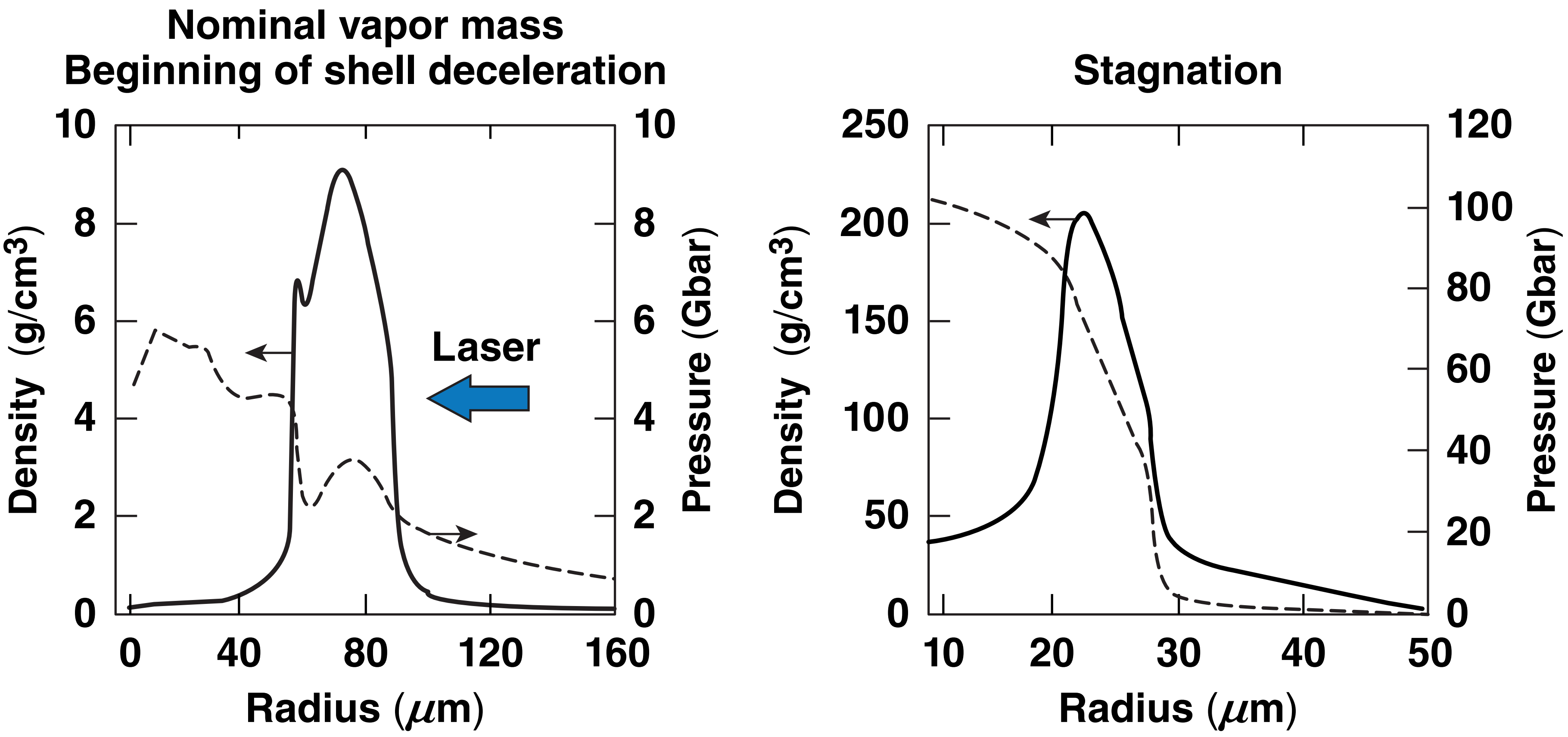




Outline

- OMEGA cryogenic target design
- Target performance
- Performance analysis using 2-D *DRACO* simulations
- **Performance degradation mechanisms**
  - **increased vapor mass**
  - **shell density relaxation caused by Rayleigh–Taylor (RT) mix and preheat**
- Conclusions

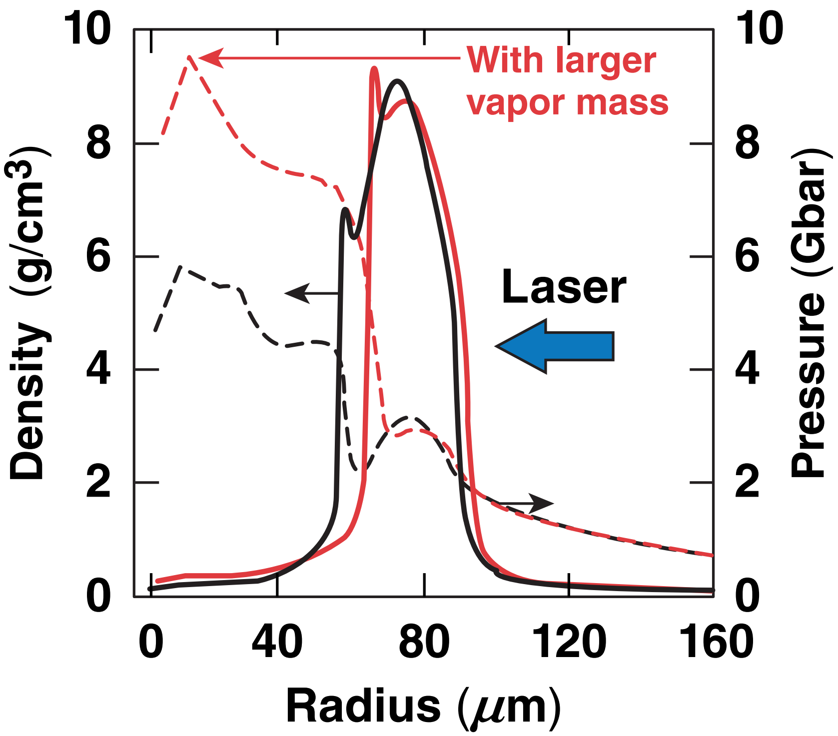
Excessive vapor mass leads to a larger hot-spot radius at stagnation



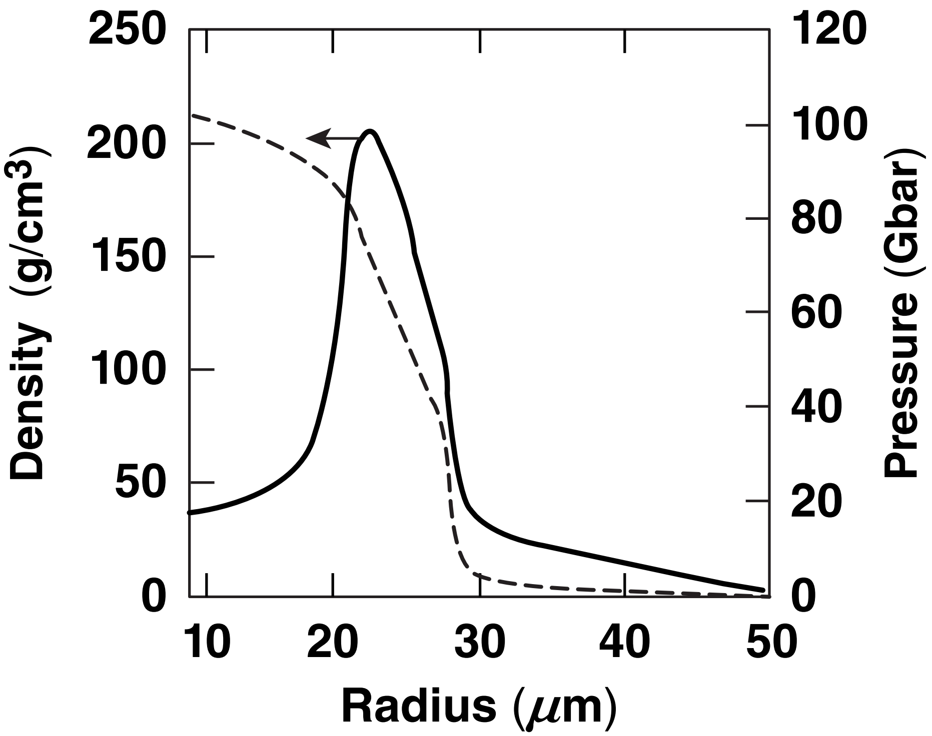
Excessive vapor mass leads to a larger hot-spot radius at stagnation

- Fuel contamination and ablator-to-vapor mix contribute to larger vapor mass

Larger vapor mass leads to stronger shell deceleration



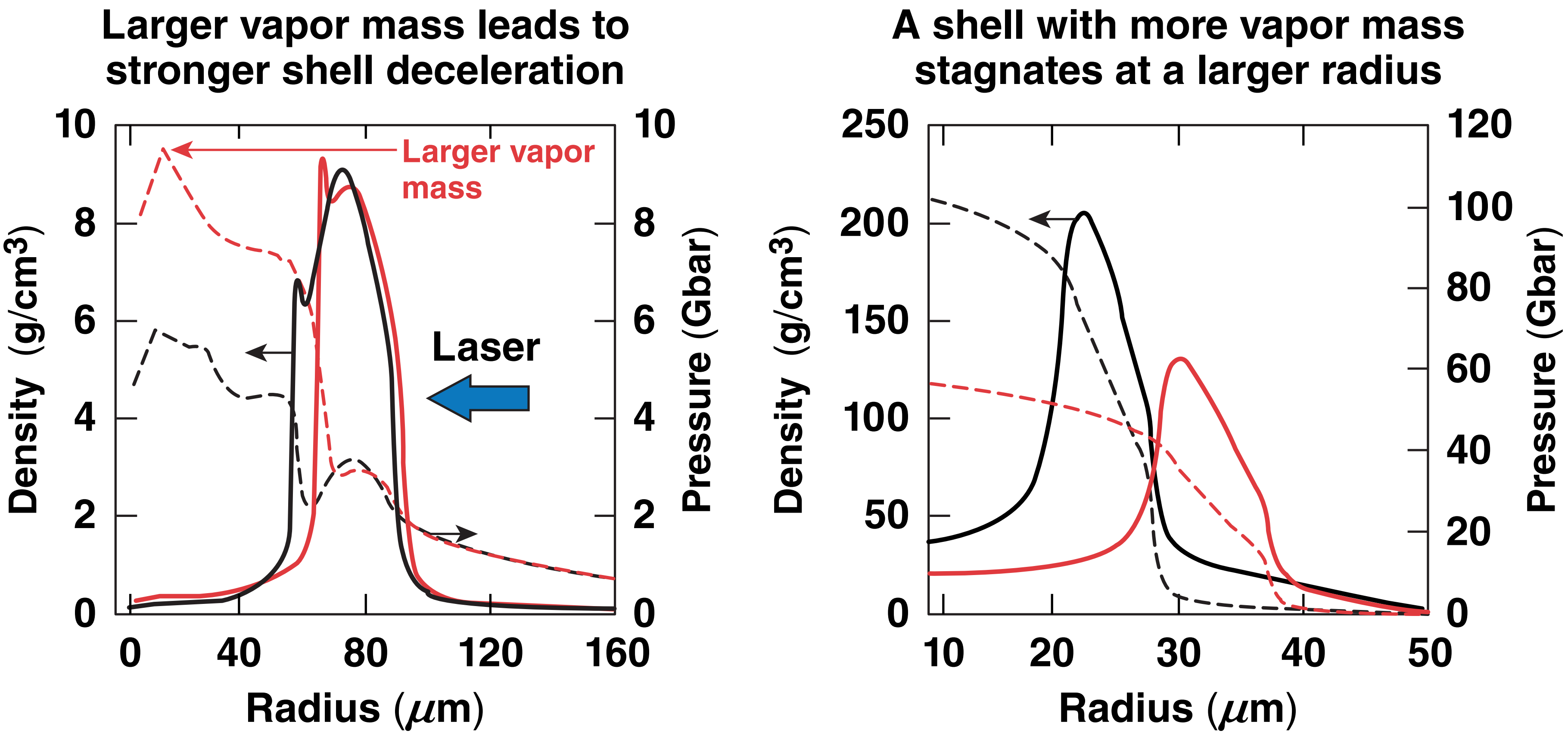
Stagnation



Degradation Mechanisms

Excessive vapor mass leads to a larger hot-spot radius at stagnation

- Fuel contamination and ablator-to-vapor mix contribute to larger vapor mass


Larger vapor mass leads to stronger shell deceleration

A shell with more vapor mass stagnates at a larger radius

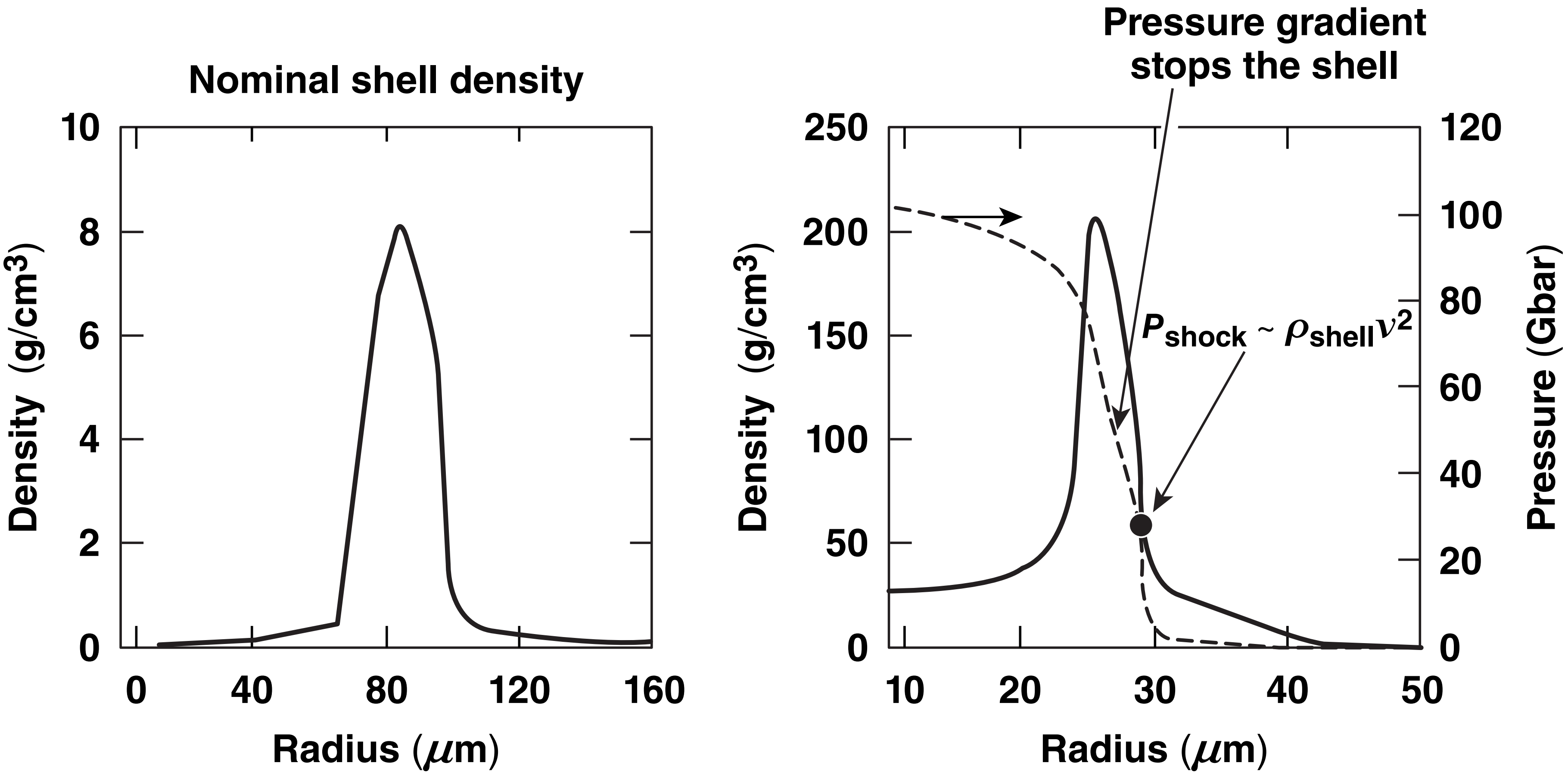
$$\rho R \sim \frac{\rho R_{\text{max}}}{\sqrt{1+\frac{m_{\text{vapor}}}{m_{\text{norm}}}}},\ P_{\text{hs}} \sim \frac{P_{\text{max}}}{\left(1+\frac{m_{\text{vapor}}}{m_{\text{norm}}}\right)^{0.8}}$$

For OMEGA targets: $m_{\text{norm}} = 0.1\ \mu g$
Vapor mass increases to 2 μg because of mix in $\alpha < 2.5$ implosions

TC10991b

Degradation Mechanisms

Reduced shell density contributes to degradation in hot-spot compression

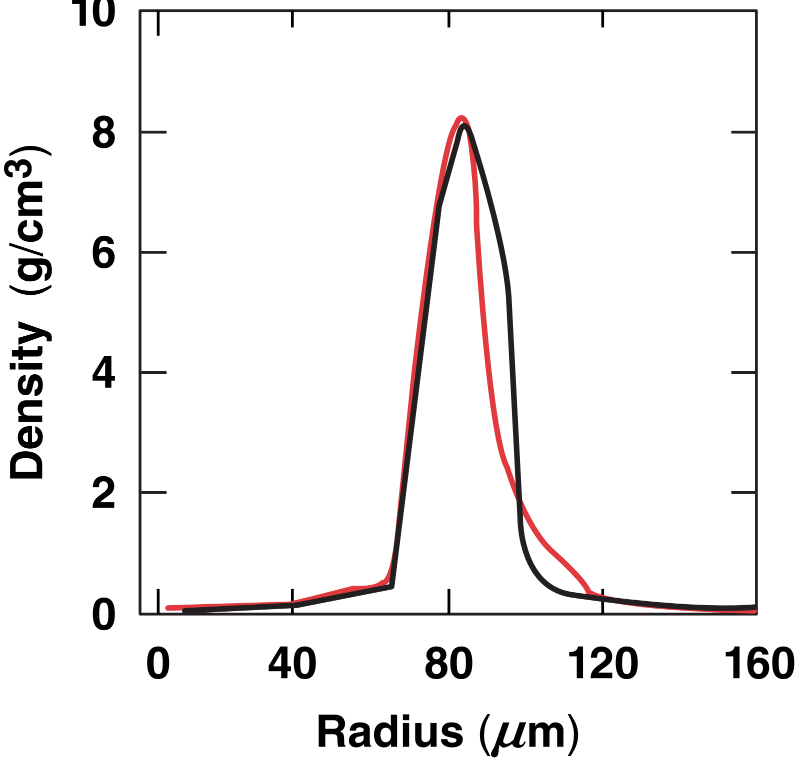


TC10992

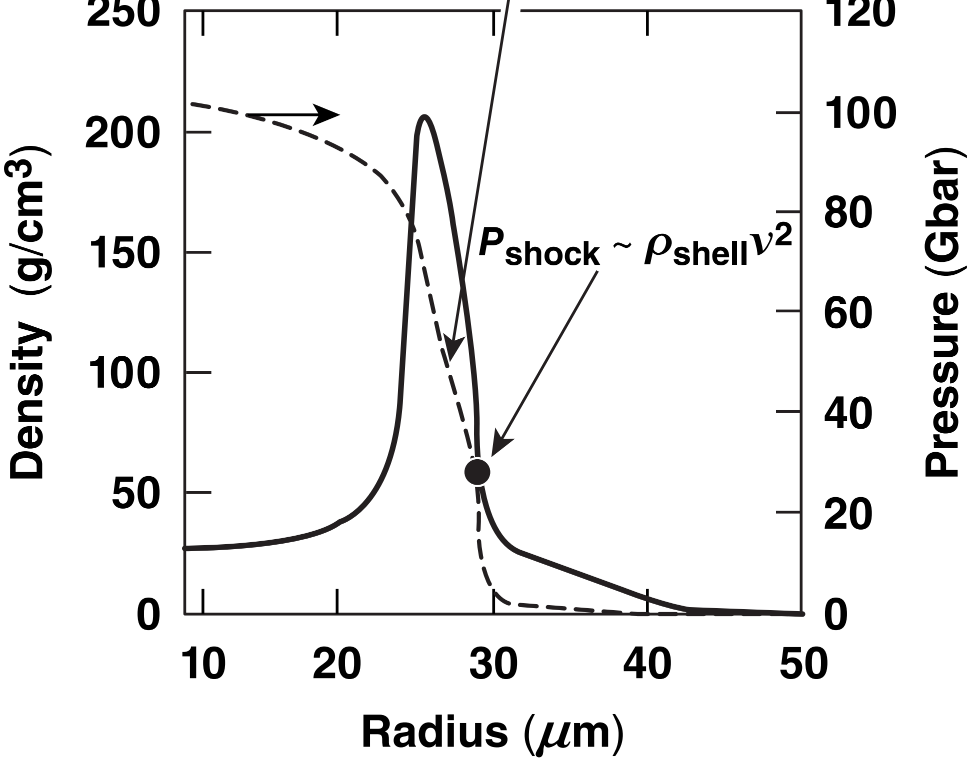
Degradation Mechanisms

Reduced shell density contributes to degradation in hot-spot compression

Shell decompression caused by instability growth at ablation front or preheat



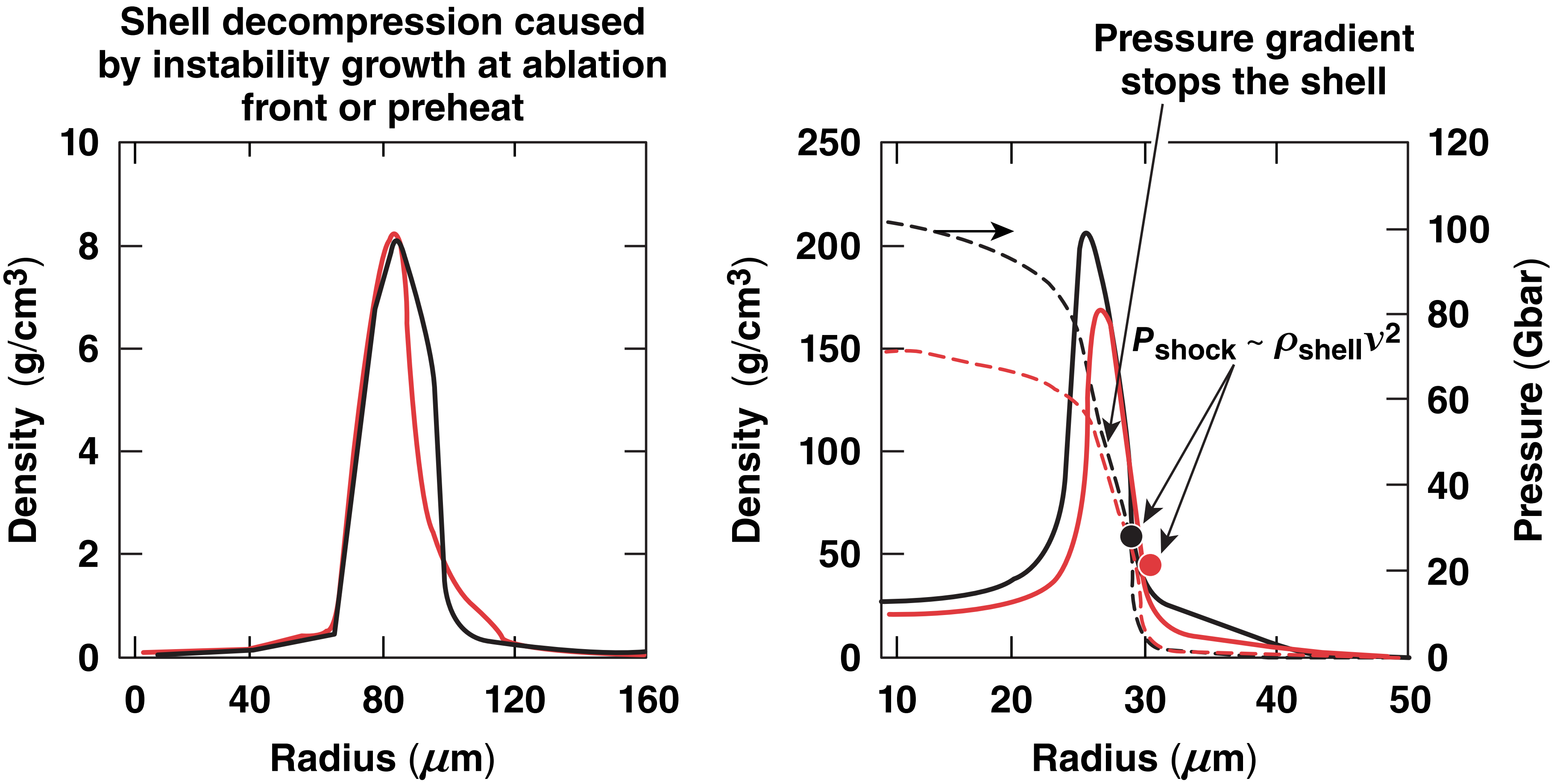
Pressure gradient stops the shell



$P_{\text{shock}} \sim \rho_{\text{shell}} v^2$

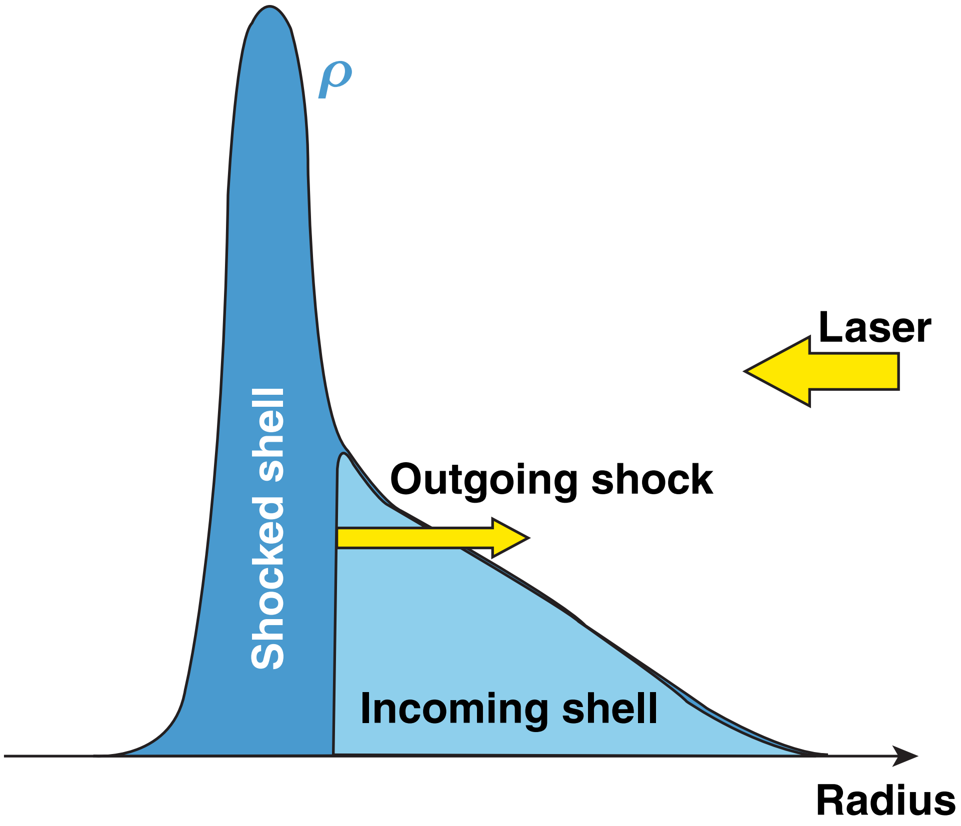
TC10992a

Reduced shell density contributes to degradation in hot-spot compression

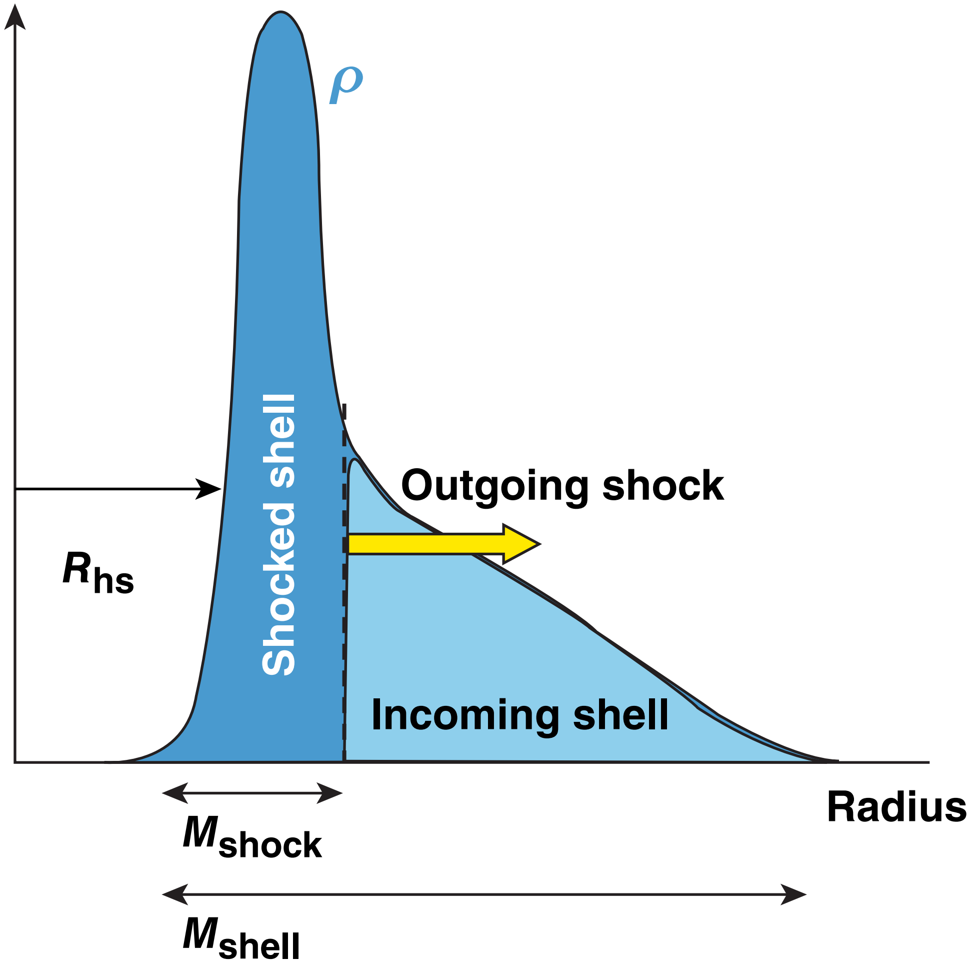


For smaller P_{shock}, lower P_{hs} stops the shell → larger stagnation hot-spot radius.

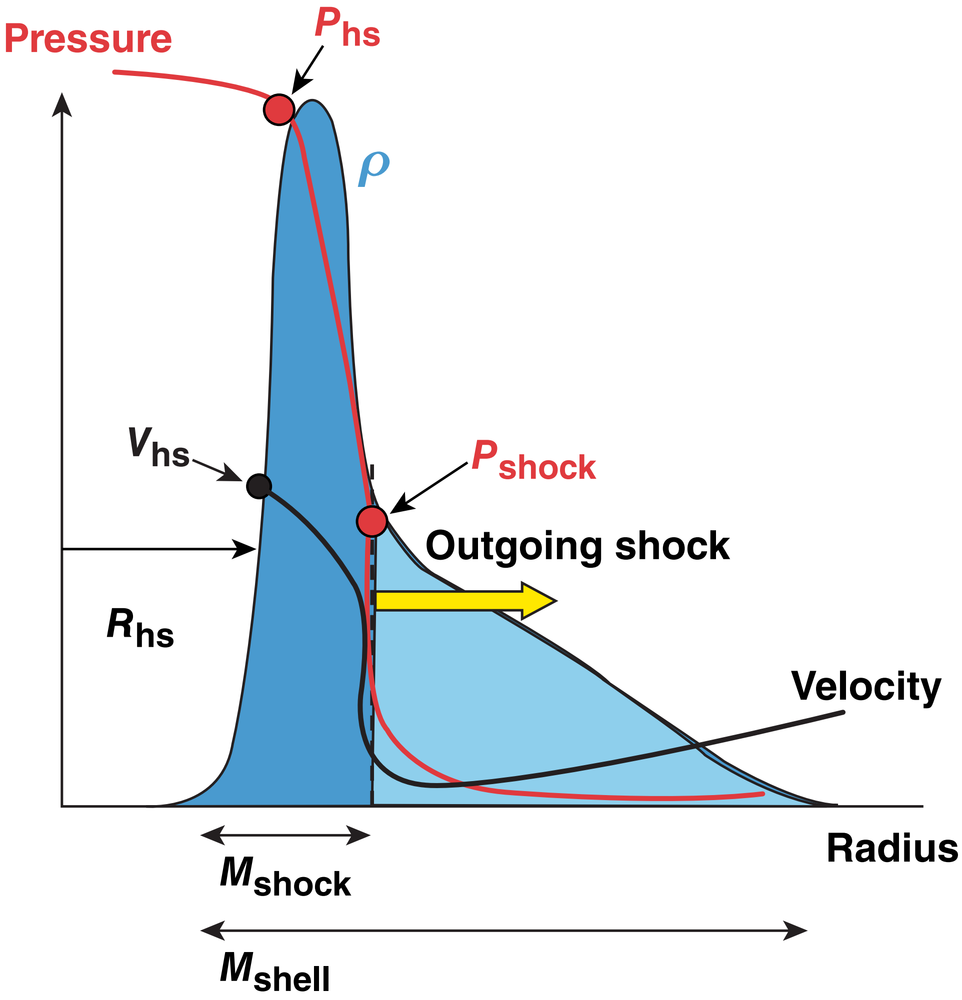
Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time



Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time

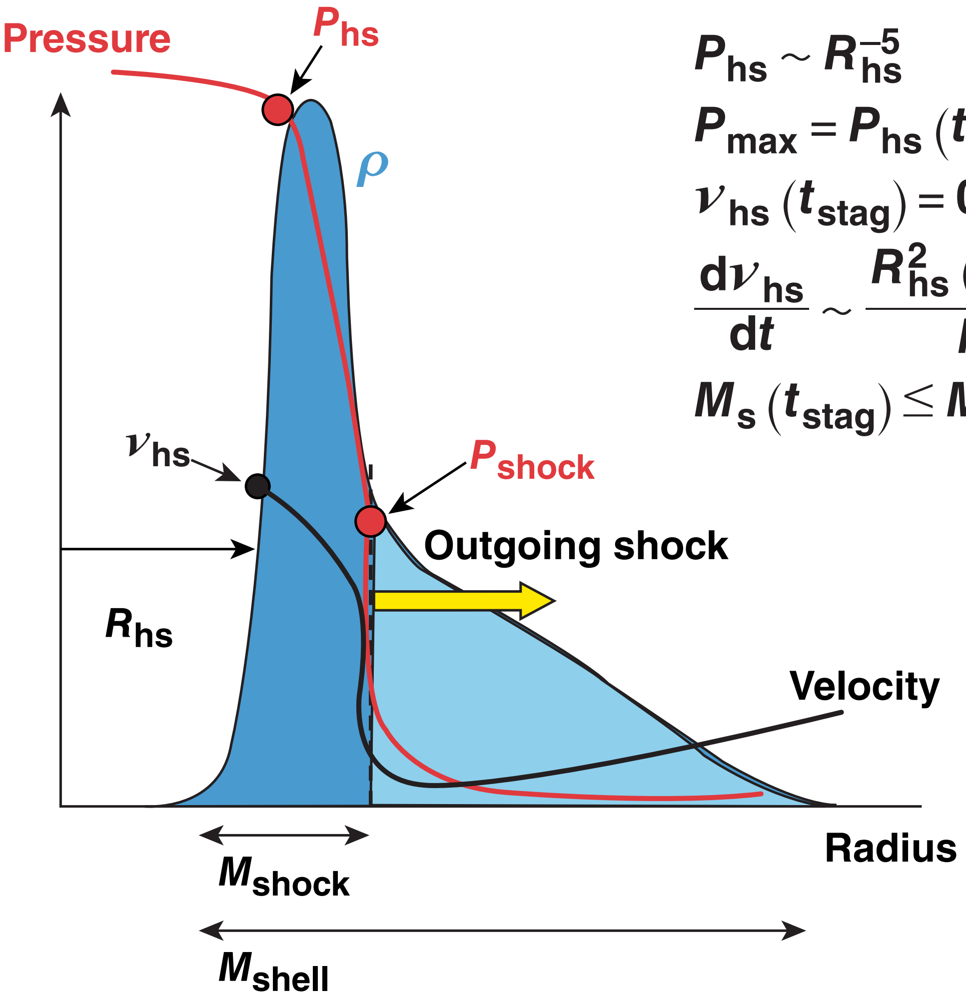


Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time



Degradation Mechanisms

Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time



$$P_{hs} \sim R_{hs}^{-5}$$

$$P_{max} = P_{hs}\left(t_{stag}\right)$$

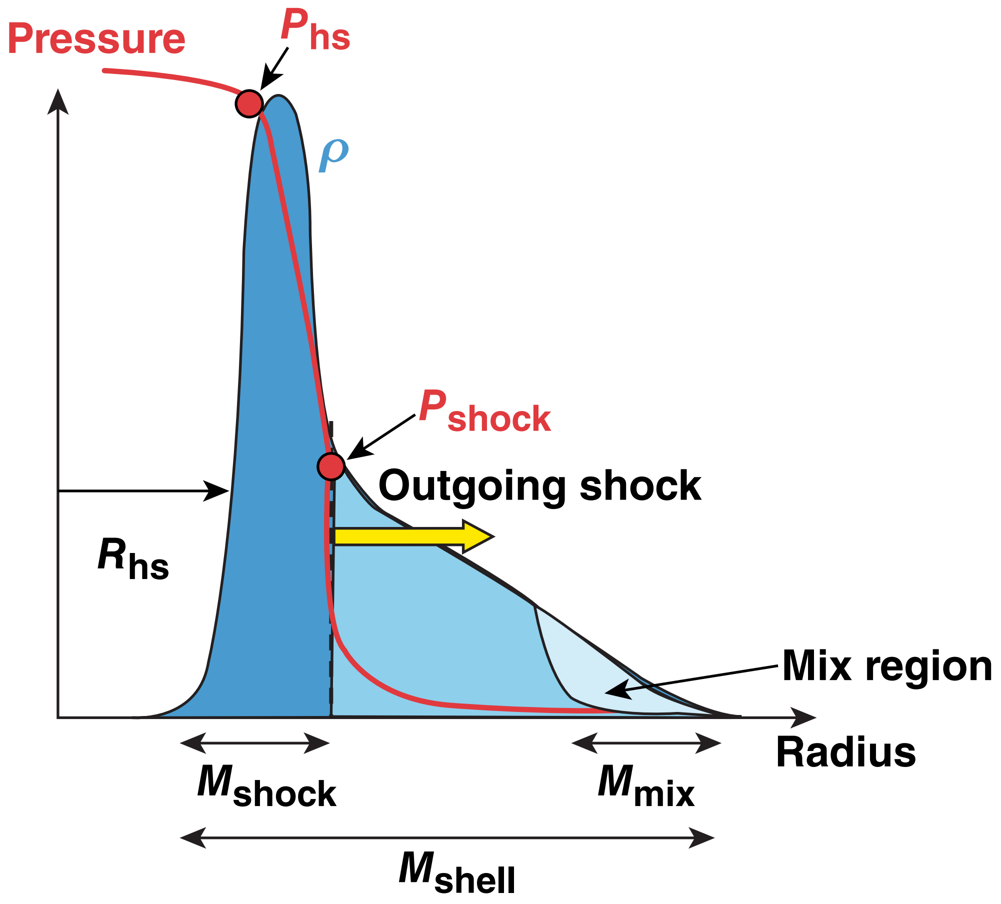
$$\nu_{hs}\left(t_{stag}\right) = 0$$

$$\frac{d\nu_{hs}}{dt} \sim \frac{R_{hs}^2\left(P_{hs} - P_{shock}\right)}{M_{shock}\left(t\right)}$$

$$M_s\left(t_{stag}\right) \leq M_{shell}$$

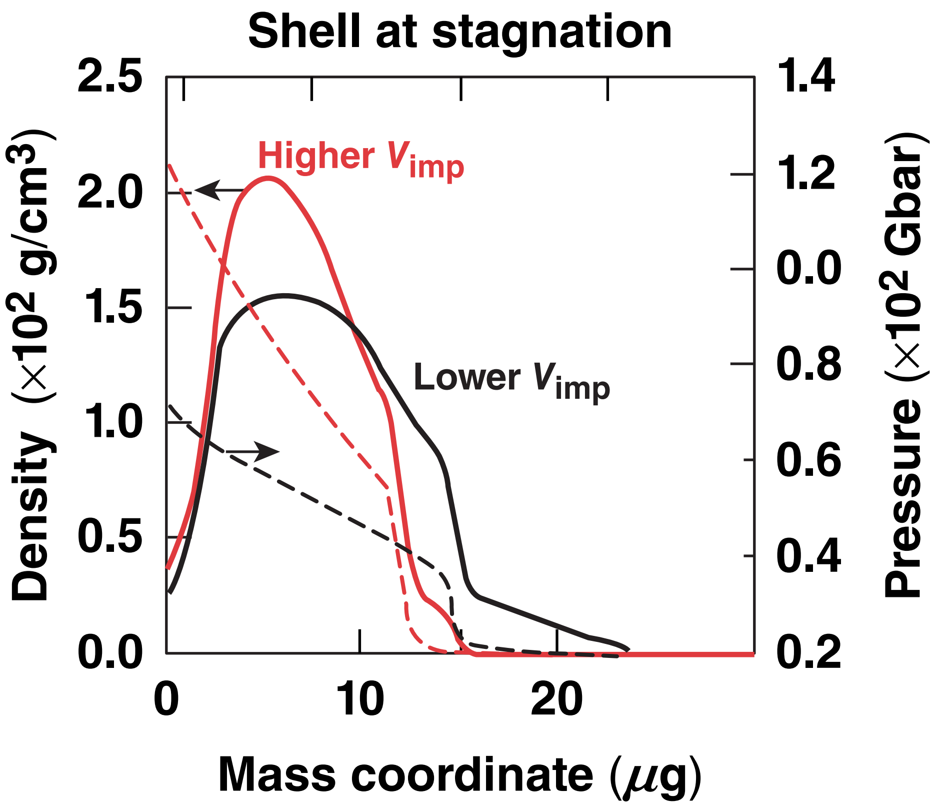
TC10993c

Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time (continued)



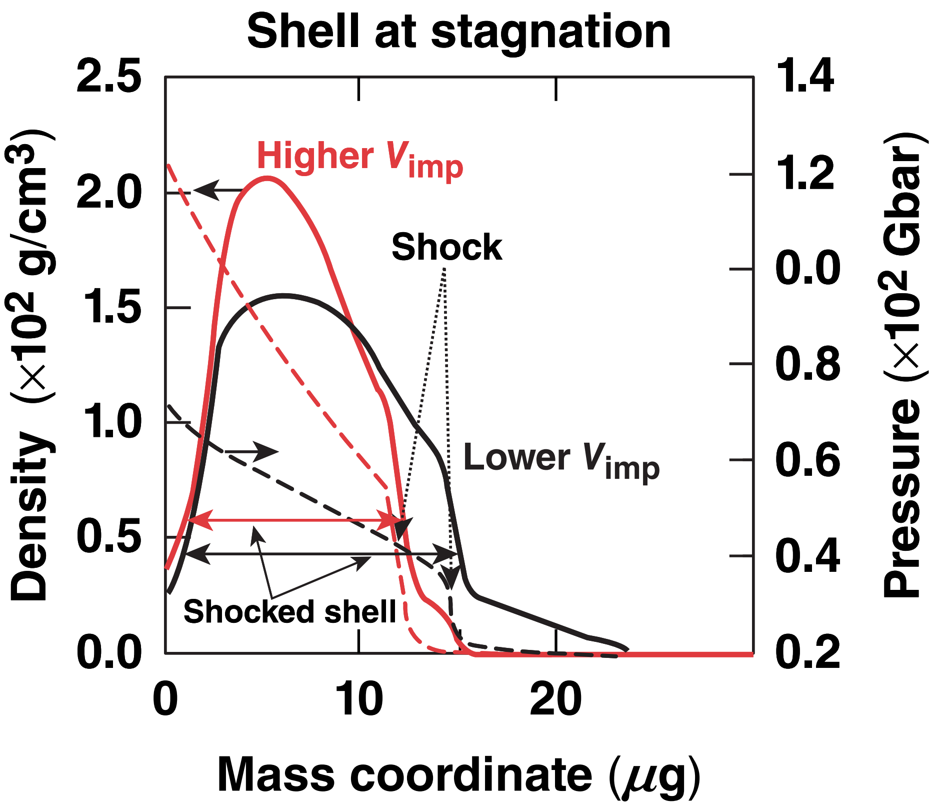
Target performance is not degraded if $M_{mix} < M_{shell} - M_{shock}(t_{stag}) = M_{unshocked}$.

Shocked-shell fraction at stagnation depends on implosion velocity, adiabat, and drive pressure



$$\frac{M_{shock}}{M_{shell}} \sim \frac{V_{imp}^{4/3}}{\alpha^{2/5} P_a^{4/15}}$$

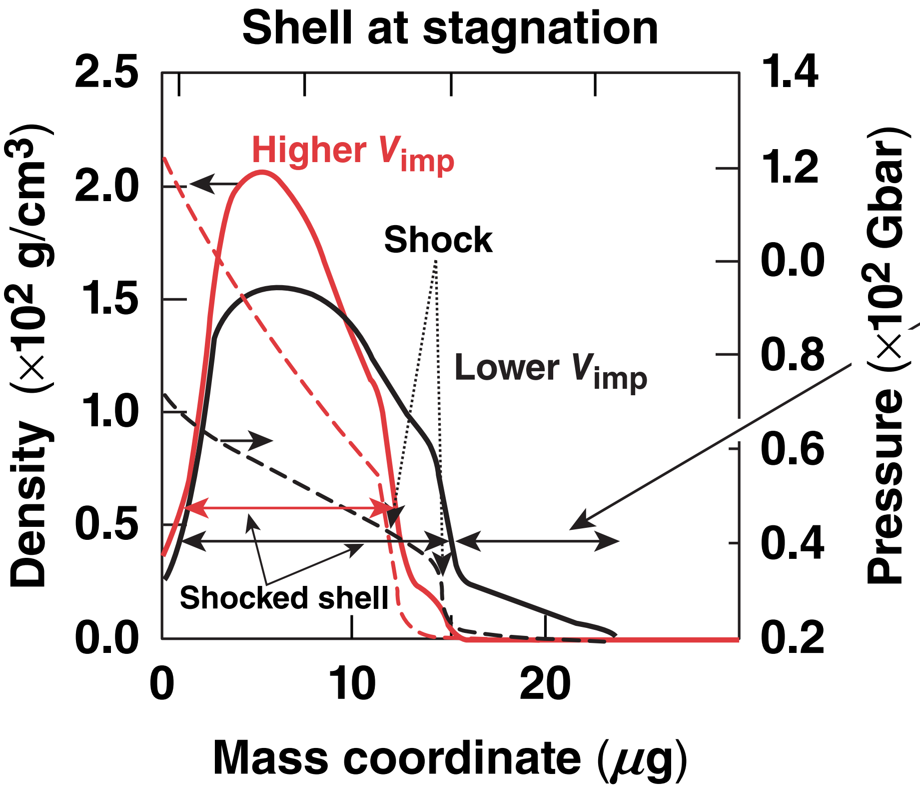
Shocked-shell fraction at stagnation depends on implosion velocity, adiabat, and drive pressure



$$\frac{M_{shock}}{M_{shell}} \sim \frac{V_{imp}^{4/3}}{\alpha^{2/5} P_a^{4/15}}$$

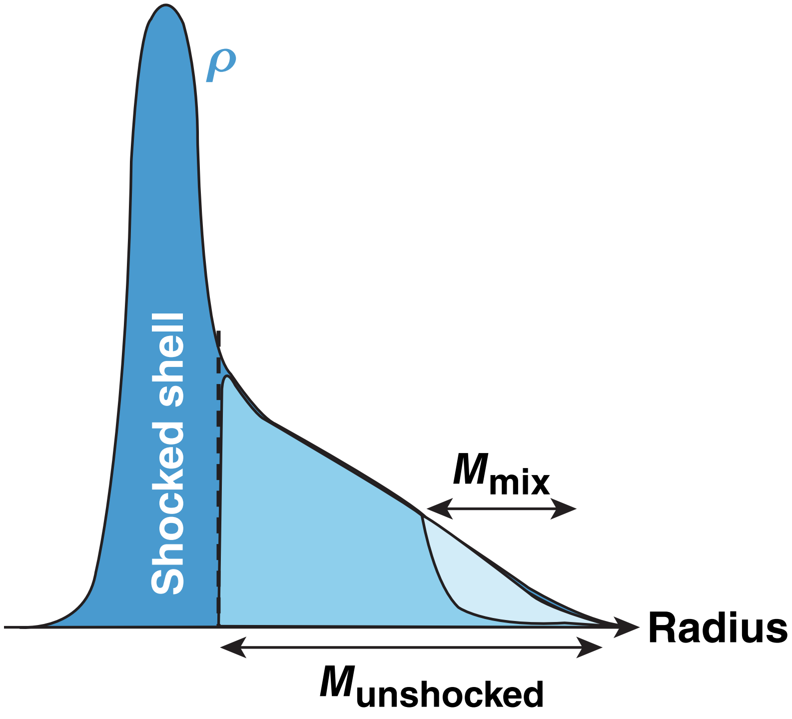
TC10994a

Shocked-shell fraction at stagnation depends on implosion velocity, adiabat, and drive pressure

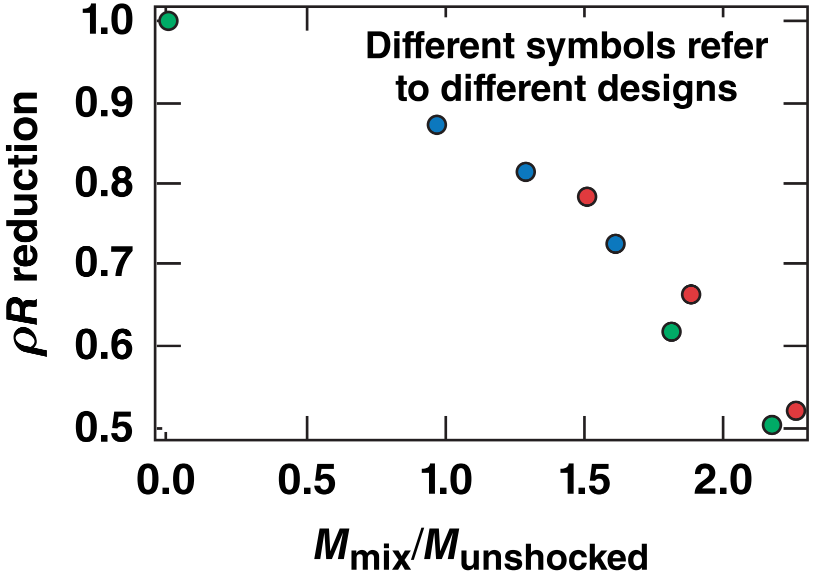


More unshocked mass, less sensitivity to RT mix at ablation front

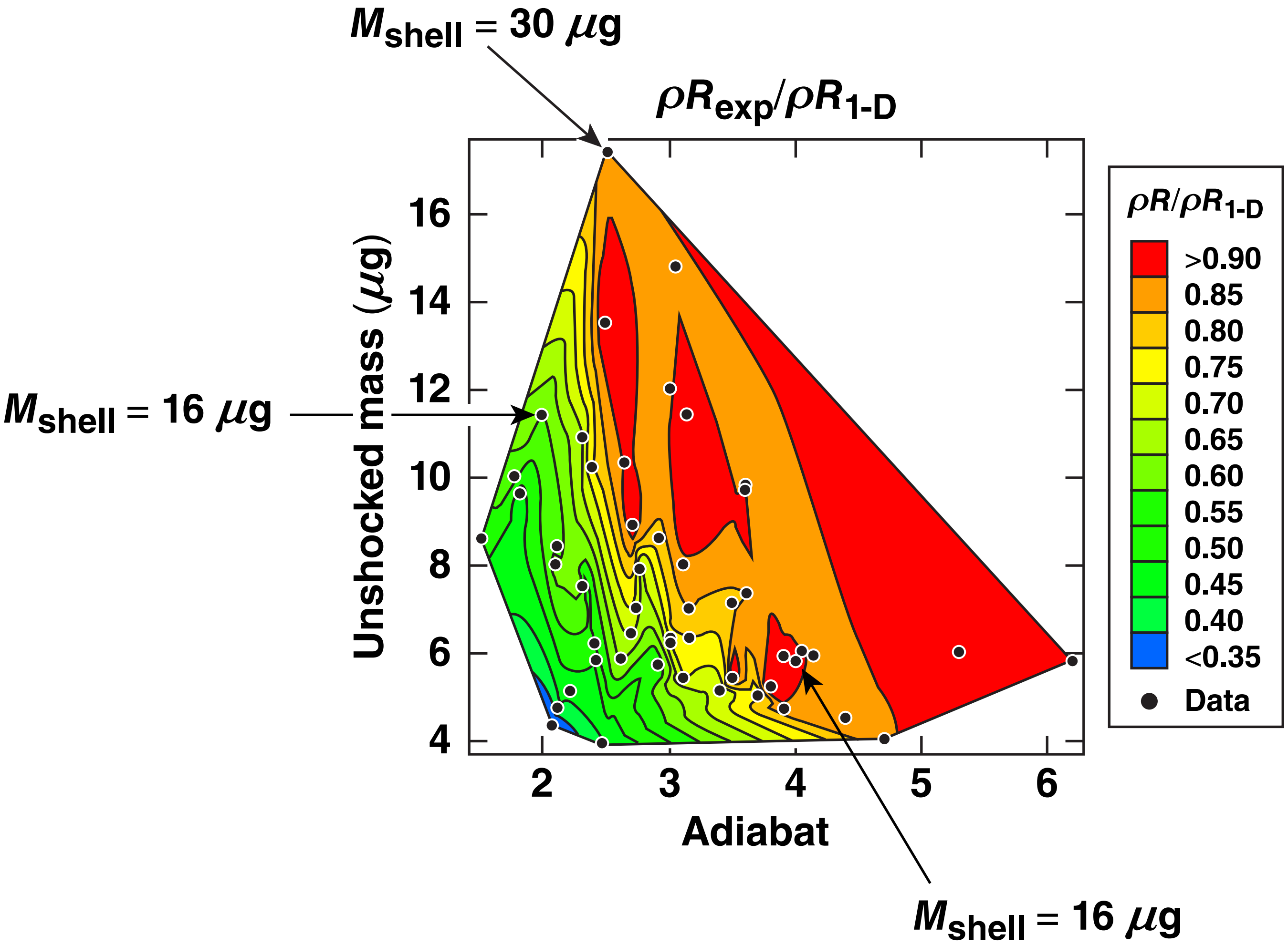
Reduction in peak areal density and pressure depends on the mass of the mix region relative to the unshocked mass



One-dimensional simulations with reduced density at the end of acceleration

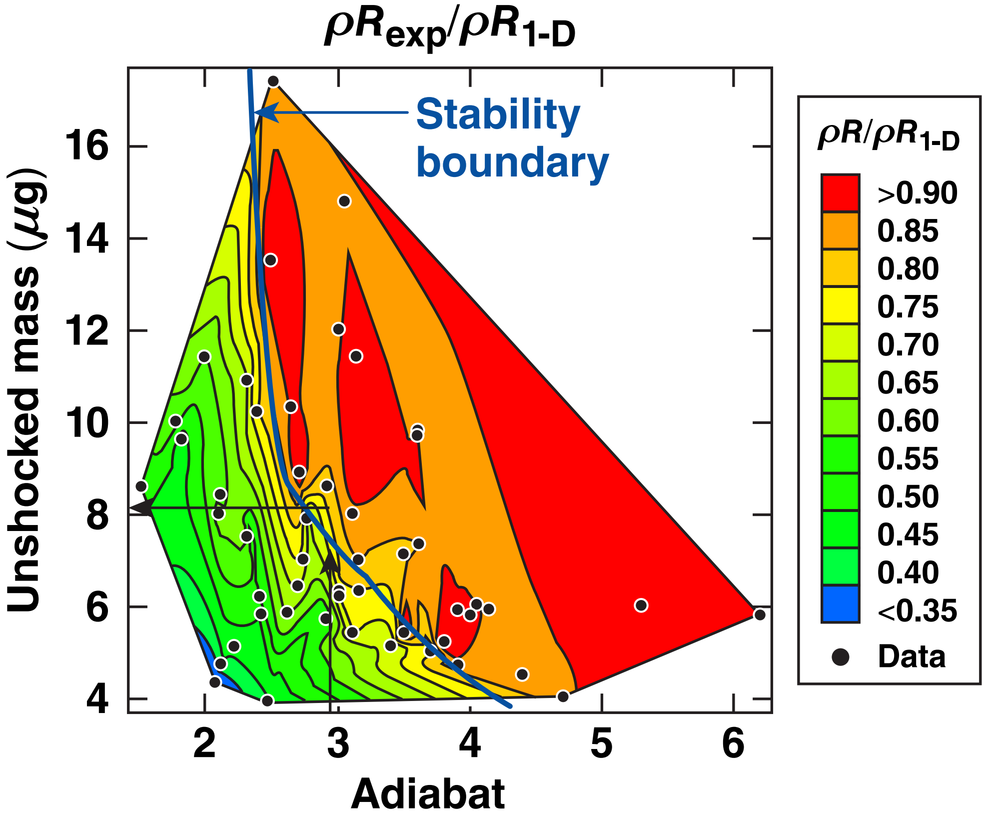


Target compression degradation is a strong function of unshocked mass at peak neutron production



Degradation Mechanisms

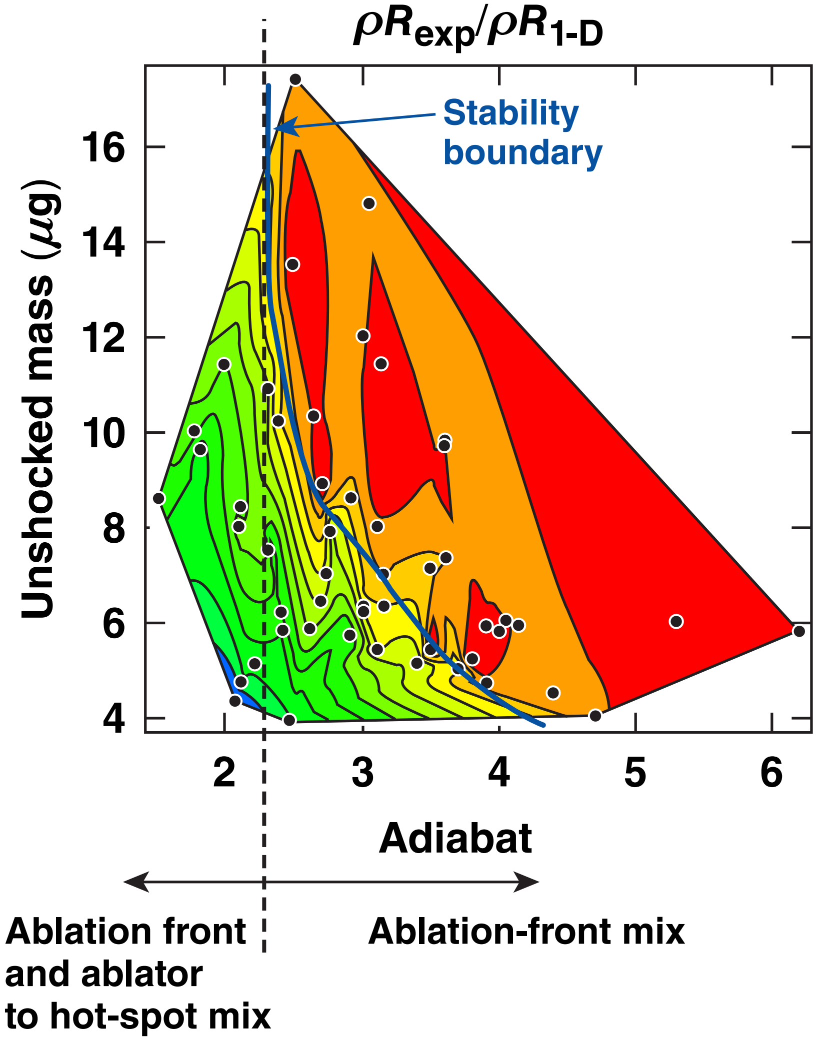
Amount of RT mix at the ablation front can be inferred from the stability boundary

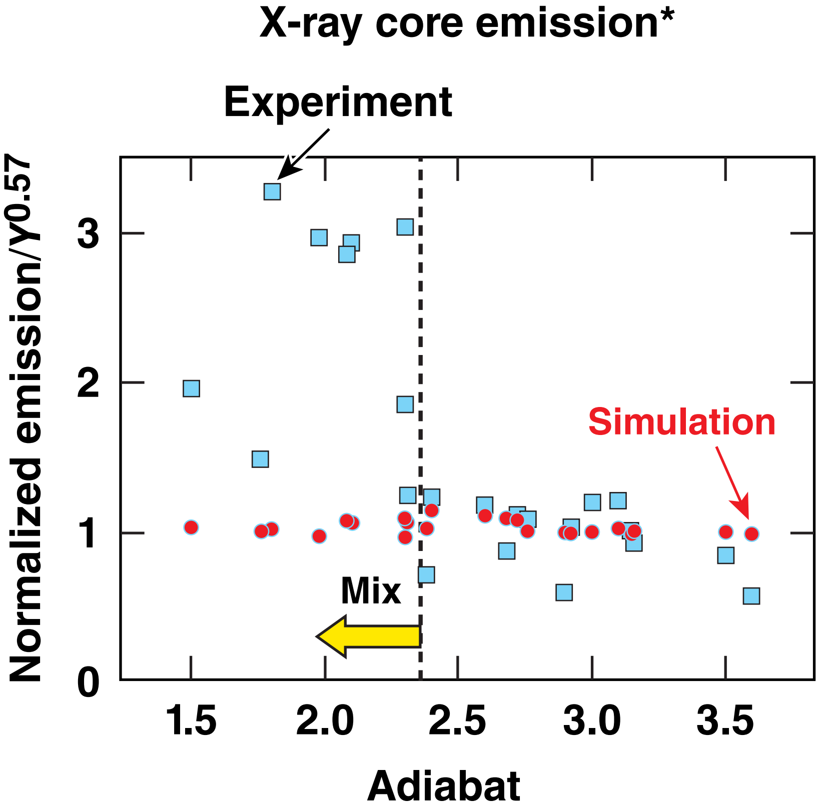


8 μg of shell is mixed at the ablation front because of a RT growth

TC10996a

Significant mix of the ablator material into the hot-spot limits performance of $\alpha < 2.5$ implosions



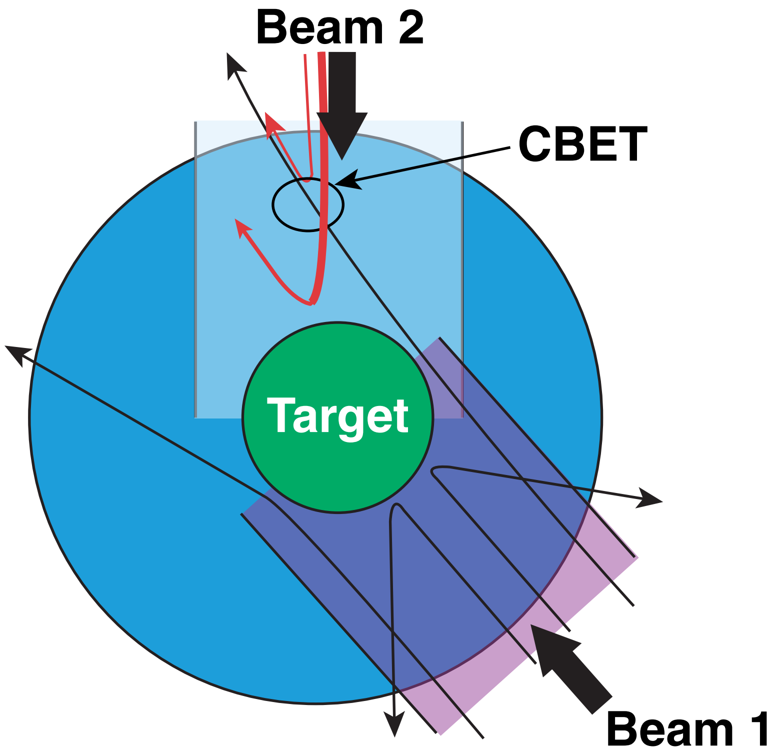


TC10996b

---

*T. C. Sangster *et al.*, Phys. Plasmas 20, 056317 (2013).

Mitigating cross-beam energy transfer* allows the shell and unshocked masses to be increased

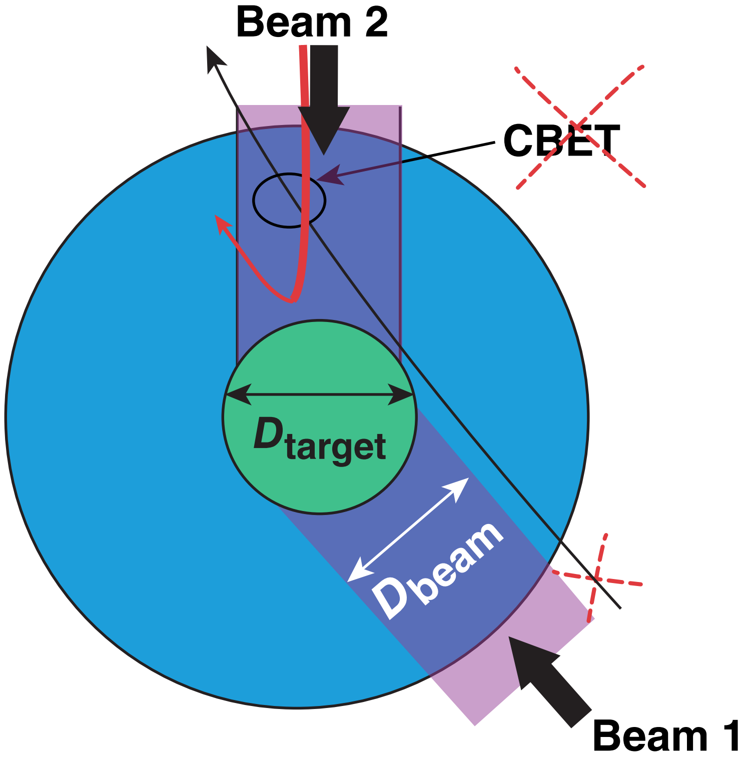


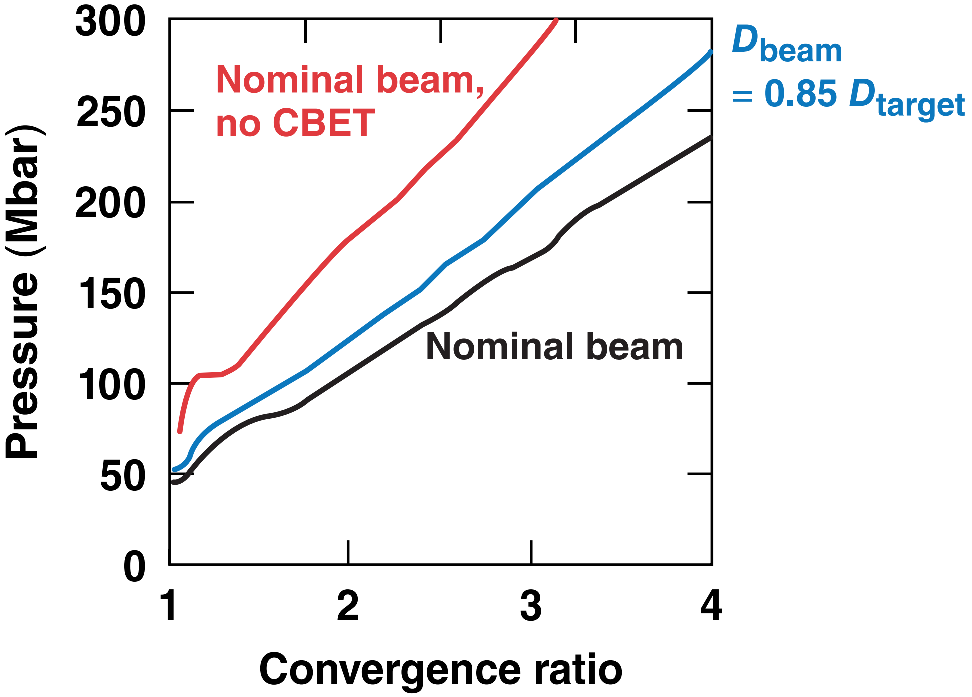
---

*I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

Mitigating cross-beam energy transfer* allows the shell and unshocked masses to increase

Using smaller beams at the main drive reduces CBET

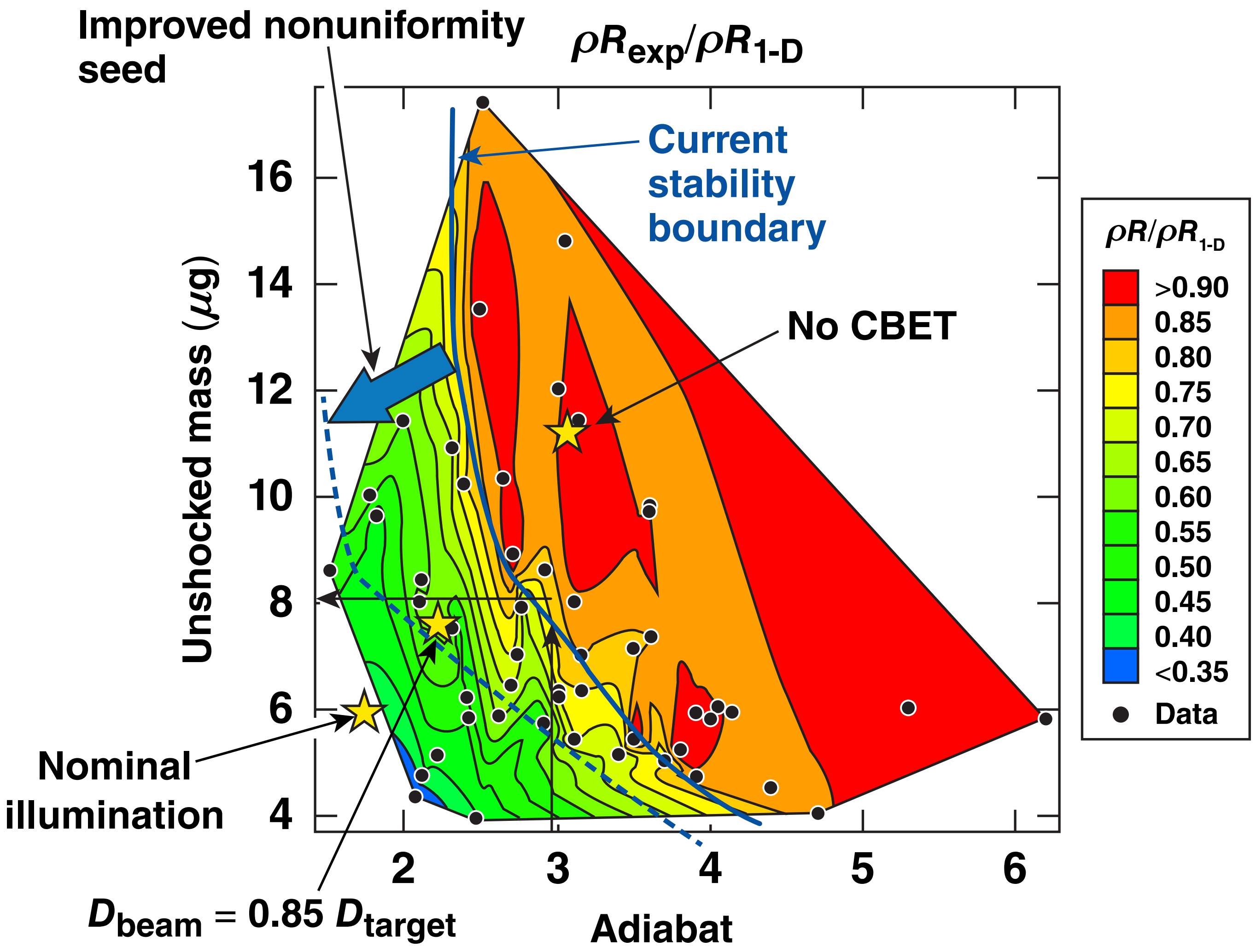




---

*I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

Mitigating CBET is required to demonstrate ignition hydrodynamic scaling on OMEGA



★ **Hydro-equivalent designs**

- Ignition hydrodynamic-equivalent OMEGA implosions require ρR ~ 300 mg/cm^2 and V_{imp} ~ 3.7 × 10^7 cm/s
- CBET mitigation strategies will be discussed in Michel, Myatt, and Froula's presentations*

---

*D. T. Michel *et al.*, NO7.00002; J. F. Myatt, FR1.00001 (invited); D. H. Froula *et al.*, CO7.00002, this conference.

Summary/Conclusions

The perturbation degradation of OMEGA cryogenic implosions is understood in terms of unshocked shell mass at stagnation

- Yields in excess of 3.4 × 10^{13} [yield-over-clean (YOC) ~ 35%] and ion temperatures up to 4 keV were measured in cryogenic implosions with $V_{\text{imp}} \sim 3.8 \times 10^7$ cm/s
- Performance degradation in moderate-adiabat ($\alpha \sim 4$) implosions is fully understood by 2-D *DRACO* simulations
- Shells in lower-adiabat implosions ($\alpha \sim 2.5$) break up during acceleration, leading to an increased hot-spot mass and reduced convergence
- The unshocked mass at peak compression determines the impact of the ablator mix

Improving shell stability and mitigating cross-beam energy transfer (CBET) are required to demonstrate ignition hydrodynamic scaling on OMEGA.