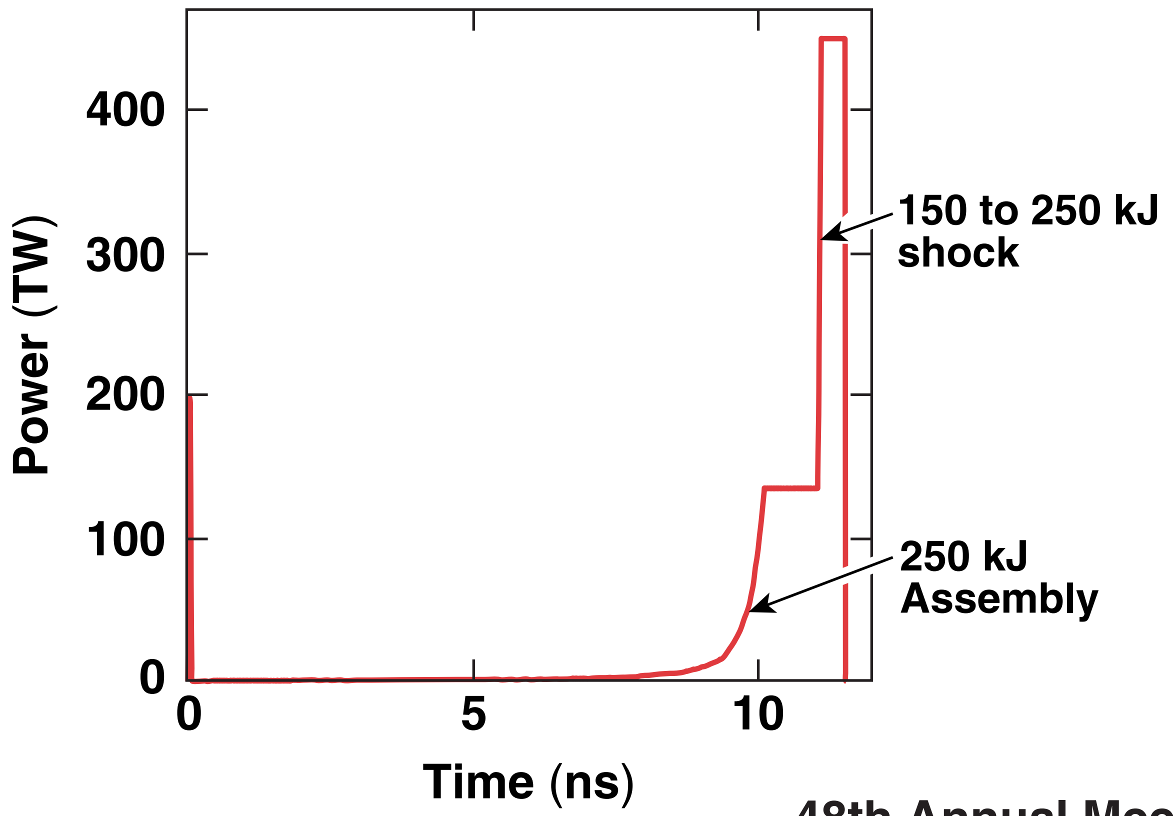
Shock Ignition of Thermonuclear Fuel with High-Areal Density

E_L = 400 to 500 kJ



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Summary

Optimal targets for shock ignition are thick shells driven on a low adiabat at low implosion velocities (and low IFAR ~20)

- A convergent shock launched by a spike in the laser intensity leads to an adiabatic compression of the hot spot and reduction of the energy required for ignition.
- The robustness of the SI scheme is measured by the size of the shock-launching-time ignition window.
- 2-D simulations indicate that shock ignition may survive the detrimental effects of laser imprinting at a relatively low driver energy (~400 to 500 kJ) leading to gains of ~50 to 80.
- Applications of SI to the NIF in following talk U02.00011 by L. J. Perkins

Significant gains are predicted with moderate driver energies.

Collaborators

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High areal densitites (ρR) and low-implosion velocities (V_i) lead to high-energy gains (assuming that ignition occurs)

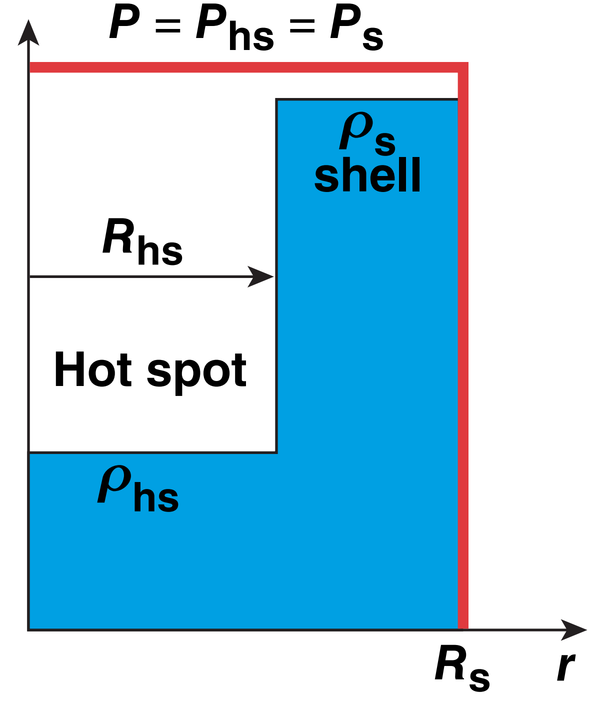
$$\boxed{G = \frac{E_{\text{fusion}}}{E_{\text{laser}}} \sim \frac{\theta}{V_i^{1.2}}}$$

$$\theta = \frac{1}{1 + 7/\rho R} = \text{burnup fraction}$$

- Higher ρR → longer burn time
- Lower V_i → more fuel mass for the same kinetic/laser energy

The hot-spot ignition condition is given by the balance of alpha heating with energy losses, including expansion losses

Isobaric fuel assembly



$$\boxed{\frac{\dot{E}_{hs}}{E_{hs}} = \frac{1}{\tau_\alpha} - \frac{1}{\tau_{rad}} - \frac{1}{\tau_{exp}} > 0}$$

$1/\tau_\alpha \sim n_{hs}^2 \langle \sigma v \rangle / P_{hs}$ alpha heating

$1/\tau_{rad} \sim n_{hs}^2 \sqrt{T_{hs}} / P_{hs}$ radiation cooling

$1/\tau_{exp} \sim \sqrt{\ddot{R}_{hs}/R_{hs}}$ expansion

$M_s \ddot{R}_{hs} = 4\pi P_{hs} R_{hs}^2$ shell Newton's law

TC7595

For isobaric fuel assemblies, the ignition condition depends only on velocity and shell areal density

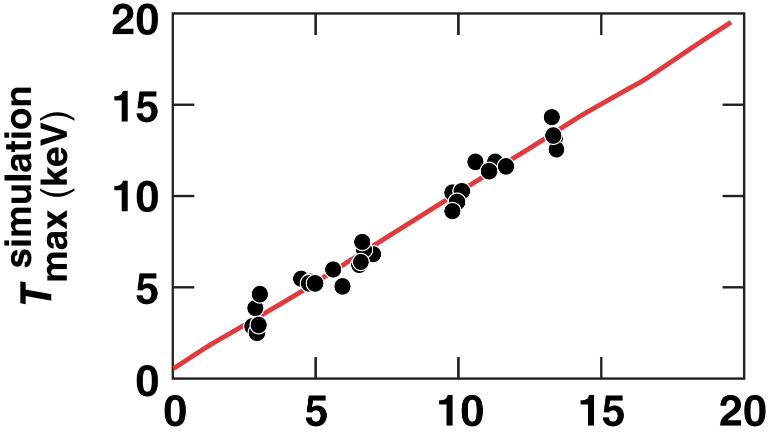
$$(\rho_s \Delta_s)^2 V^2 \left(T_{\text{keV}}^{\text{isob}} - 4.4\right) > \text{const}$$

- V_{min} is the minimum velocity required to overcome radiative losses ~1.5×10^7 cm/s.

$$(\rho_s \Delta_s)^2 V^2 \left[\left(\frac{V}{V_{\text{min}}}\right)^{1.4} - 1\right] > \text{const}$$

For $V >> V_{\text{min}}$

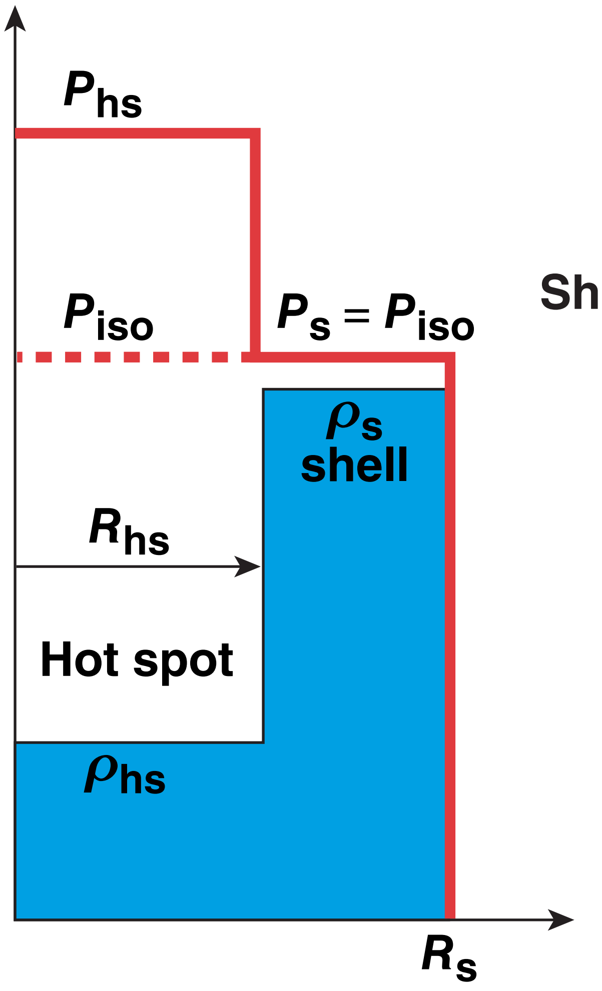
$$(\rho_s \Delta_s) > \frac{\text{const}}{V^{1.7}}$$



$$T_{\text{hot spot}}^{\text{max}} (\text{keV})^{\text{fit}} = 7\left[\frac{V_i\,(\text{cm/s})}{3 \times 10^7}\right]^{1.4}$$

Ignition requirements set a threshold for the shell areal density.

The ignition condition can be modified to include the effect of a non-isobaric fuel assembly



$$\hat{\phi}\,(\rho_s \Delta_s)^2_{iso} \quad V^2 \left(\hat{\phi}^{0.3} \left(\frac{V}{V_{min}} \right)^{1.4} - 1 \right) > \mathrm{const}$$

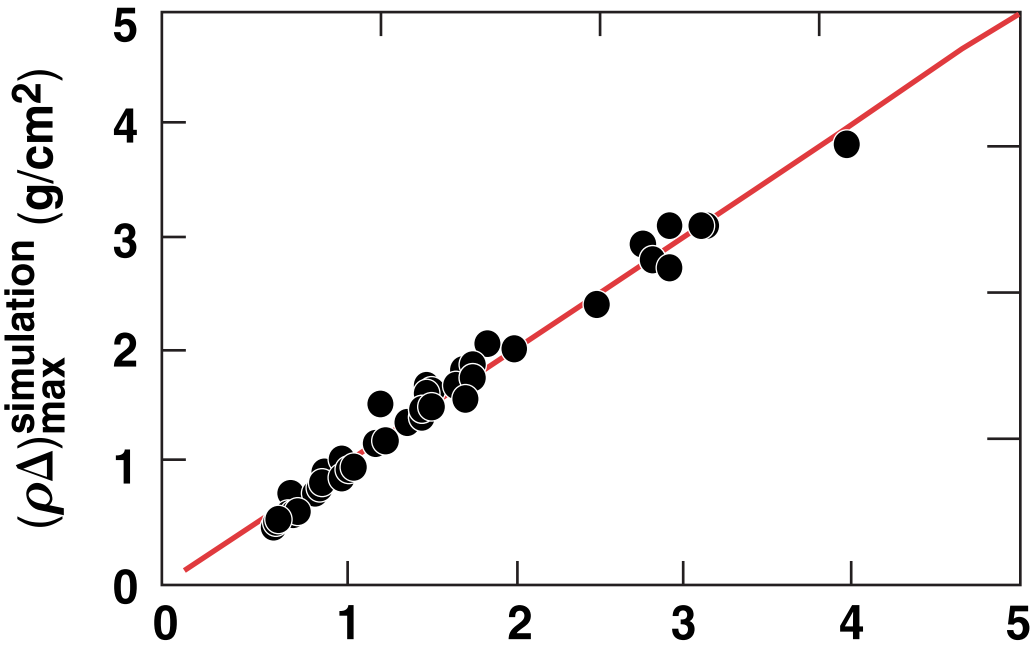
Shell areal density

Implosion velocity

Non-isobaric enhancement

$$\hat{\phi} \equiv \frac{P_{hs}/R_{hs}}{P_{iso}/R_{iso}}$$

The areal density depends on energy and adiabat



$$(\rho\Delta)_{\max}^{\text{fit}} = \frac{1.2}{\alpha^{0.57}}\left(\frac{E_L\,(\text{kJ})}{100}\right)^{0.33}\left(\frac{V\,(\text{cm/s})}{3\times10^{7}}\right)^{0.1}\ \text{g/cm}^2$$

R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).
C. Zhou, BO3.00003

The ignition threshold can be lowered in non-isobaric fuel assemblies

$$E_{ign}^{min} = \text{const} \times \frac{\alpha^{1.8}}{V^{5.4}} \frac{1}{\hat{\phi}^2} + E^{non-isob}$$

Recover Herrmann *et al*. scaling for $\hat{\phi} = 1$, $E^{\text{non-isob}} = 0$

$$\hat{\phi}^2 \sim \left(\frac{P_{hs}/R_{hs}}{P_{iso}/R_{iso}} \right)^2 \sim \left(\frac{R_{iso}}{R_{hs}} \right)^{12}$$

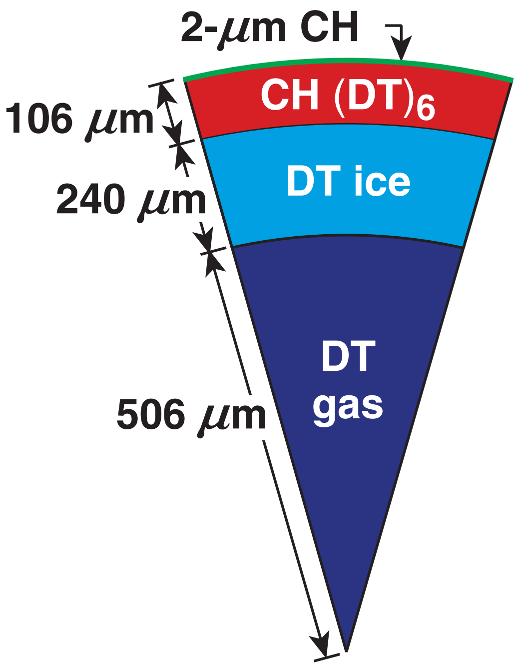
For adiabatic compression of the hot spot

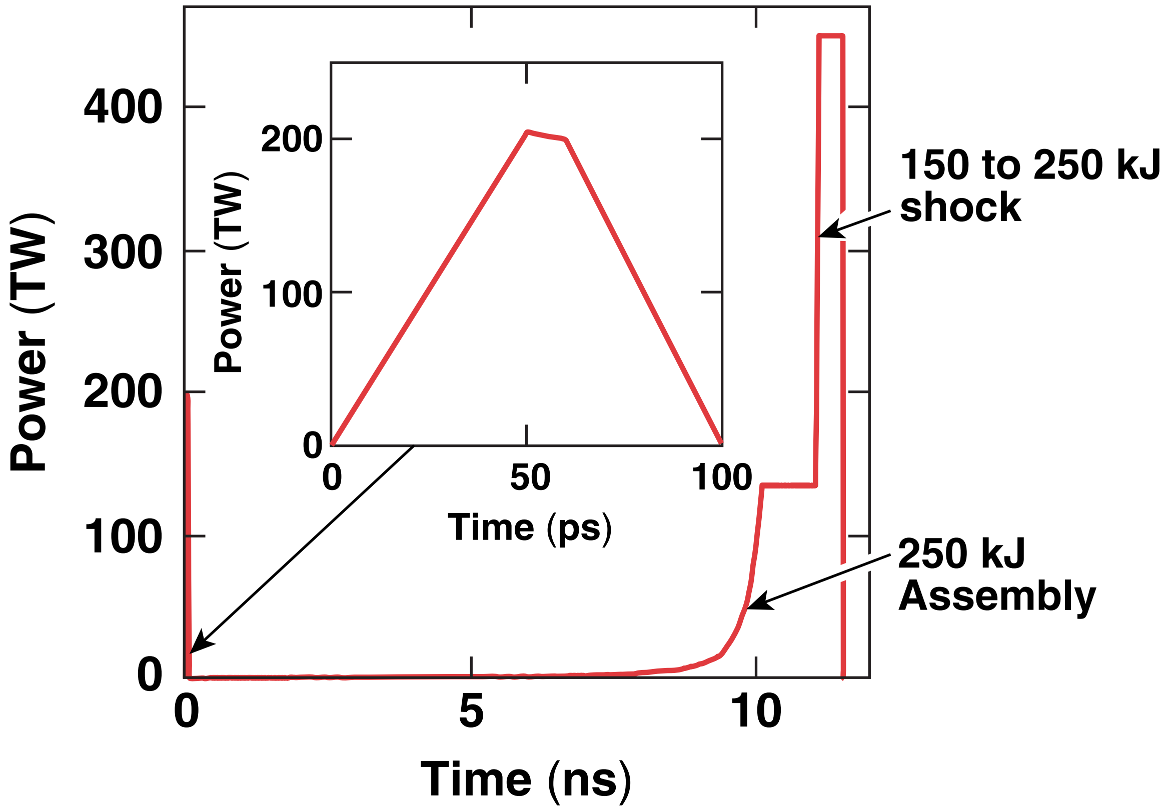
Large improvements for small reductions of the hot-spot radius.

M. Herrmann, M. Tabak, and J.D. Lindl, Nucl. Fusion 41, 99 (2001).

Non-isobaric enhancement is achieved through a convergent shock; the ignitor shock is launched by a spike of the laser intensity

E_L = 400 to 500 kJ, $V_i = 2.4 \times 10^7$ cm/s, α = 0.7 to 1.0

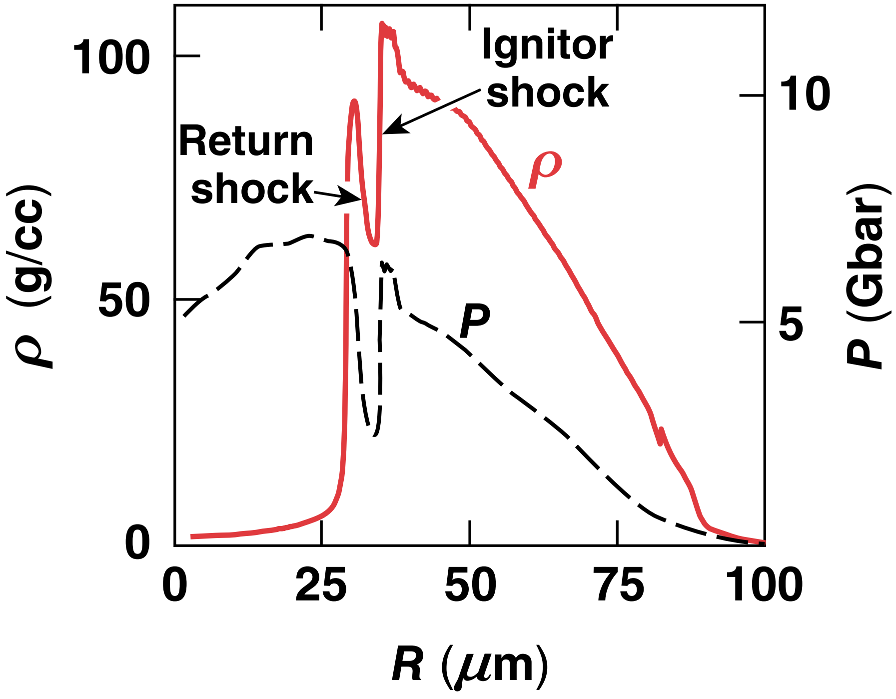




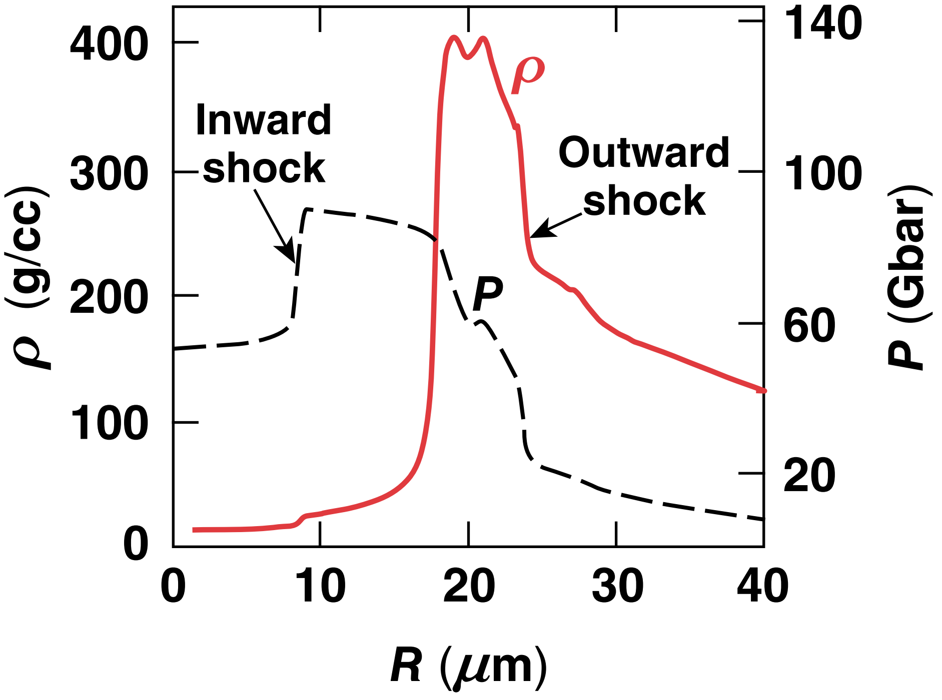
IFAR ≈ 18

Minimum shock energy for ignition = 50 kJ

The shock resulting from the collision of the ignitor and return shock compresses the hot spot

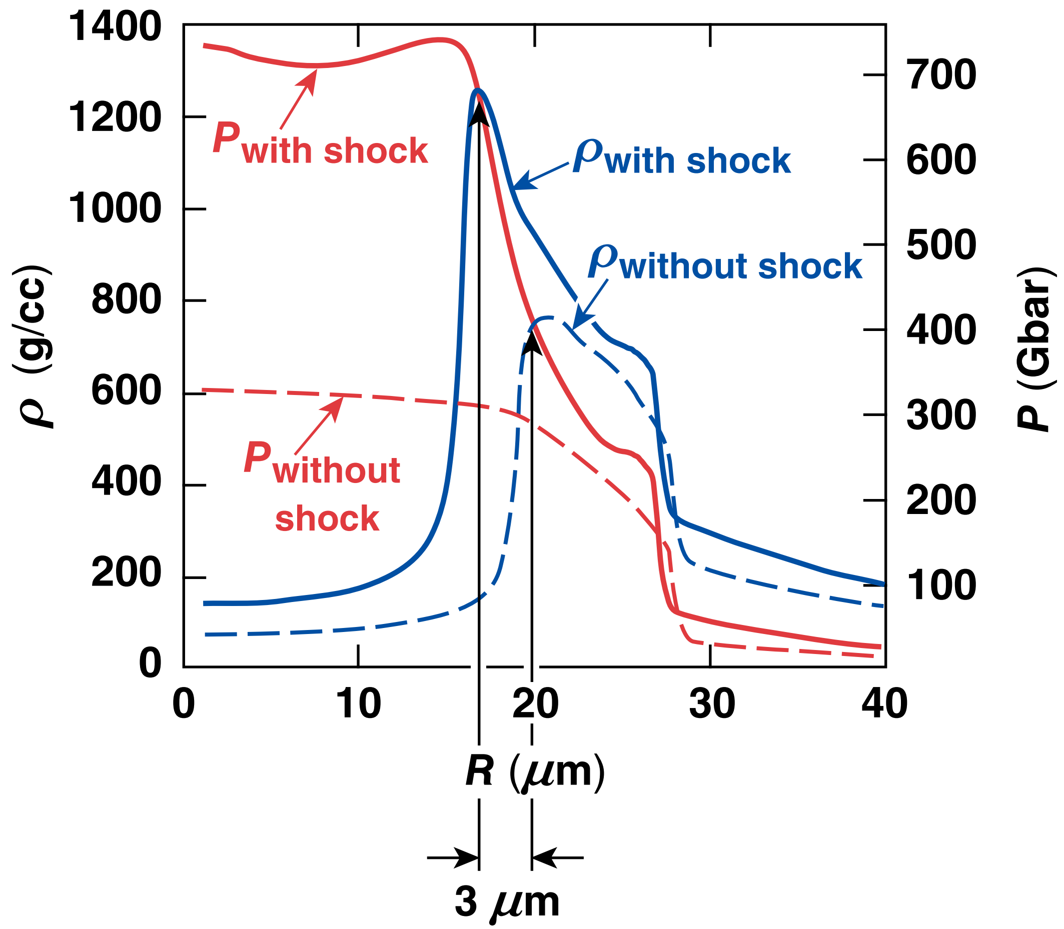


Before collision



After collision

The shock-induced compression of the hot spot is adiabatic; the ignition condition is improved



The shock compression is adiabatic

$$P_{\text{shock}} = \overset{340}{P_{\text{no shock}}}\left(\frac{\overset{20}{R_{\text{no shock}}}}{R_{\text{shock}}}\right)^{5} \quad 17$$

$$P_{\text{shock}} = 720 \text{ Gbar}$$

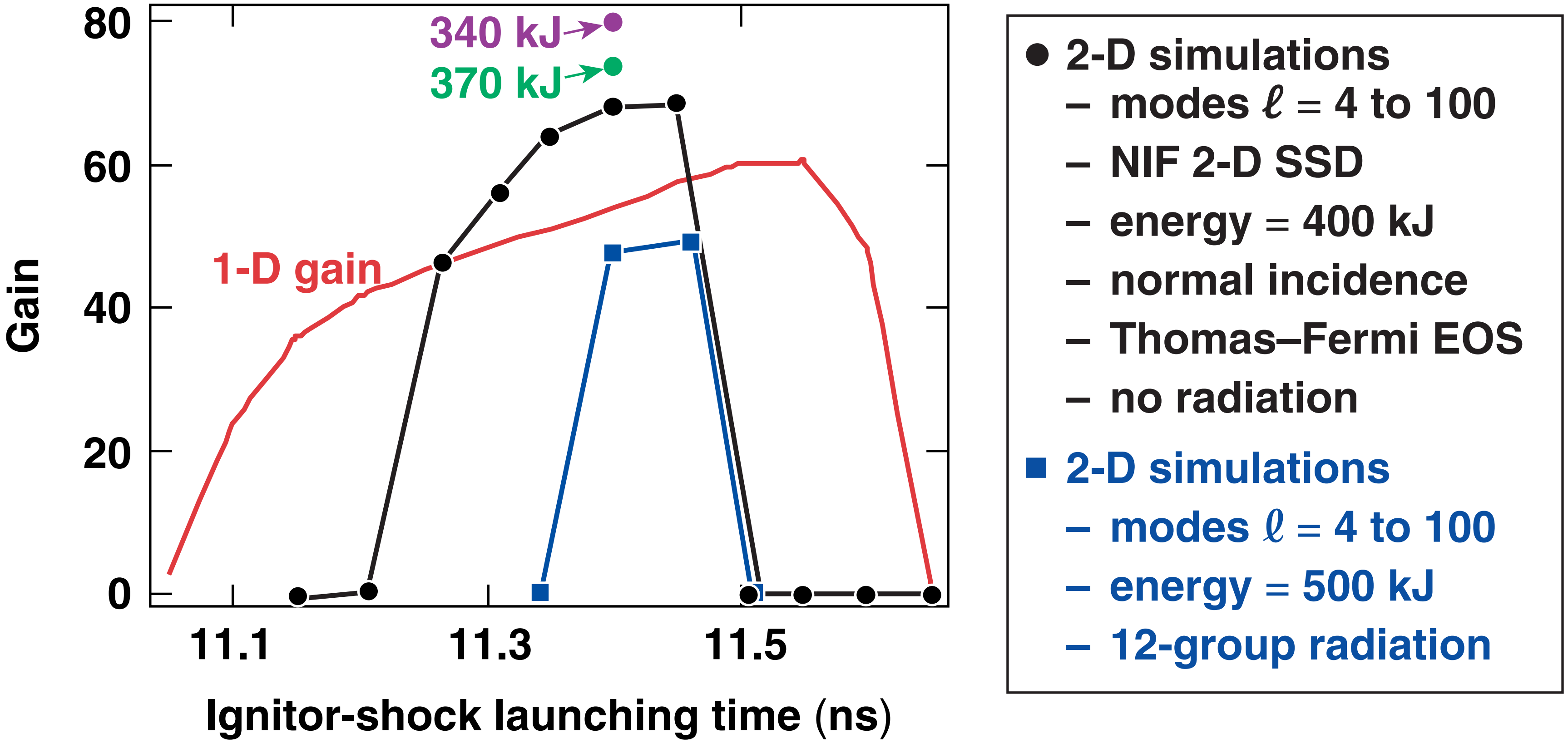
Non-isobaric enhancement

$$\hat{\phi}^2 = 7$$

Reduction of the energy required for ignition for a "free" shock

TC7602

The robustness of the ignition is measured by the size of the shock-ignition window



- ● 2-D simulations
  - – modes ℓ = 4 to 100
  - – NIF 2-D SSD
  - – energy = 400 kJ
  - – normal incidence
  - – Thomas–Fermi EOS
  - – no radiation
- ■ 2-D simulations
  - – modes ℓ = 4 to 100
  - – energy = 500 kJ
  - – 12-group radiation

Summary/Conclusions

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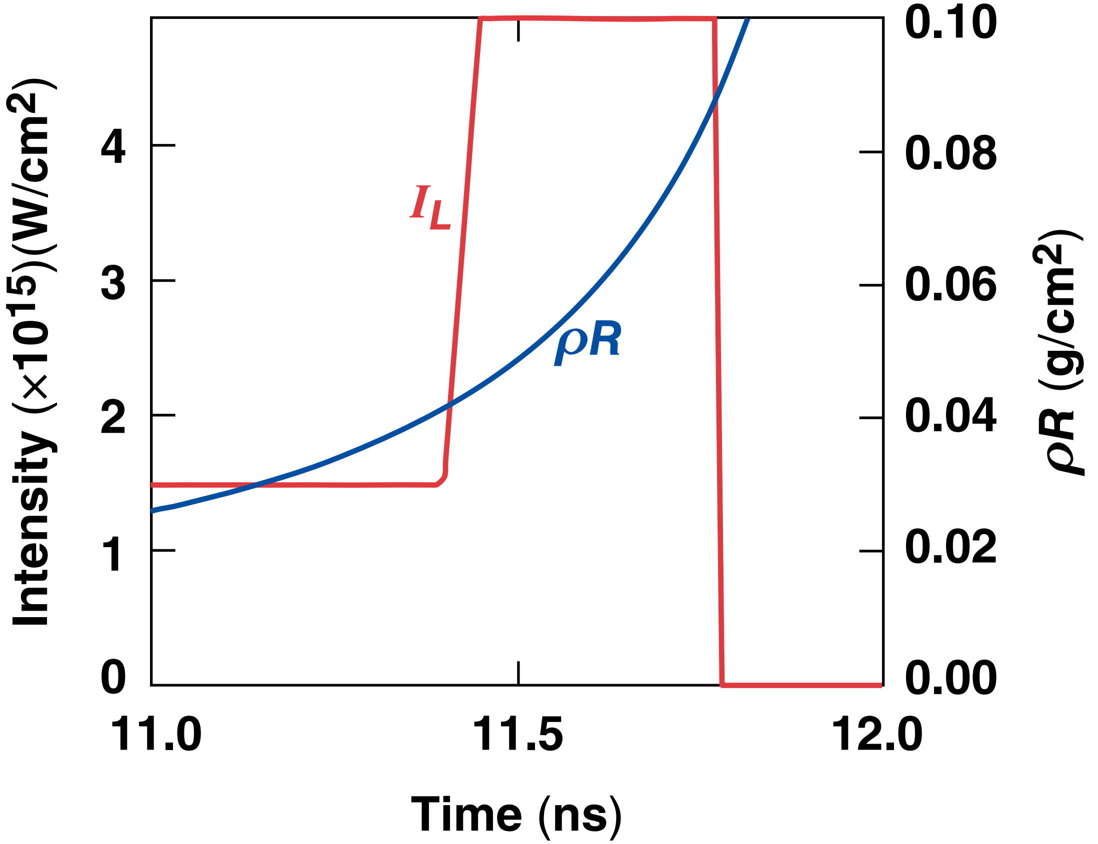
Hot electrons with energies <100 keV slow down on the shell’s outer surface



Electron penetration