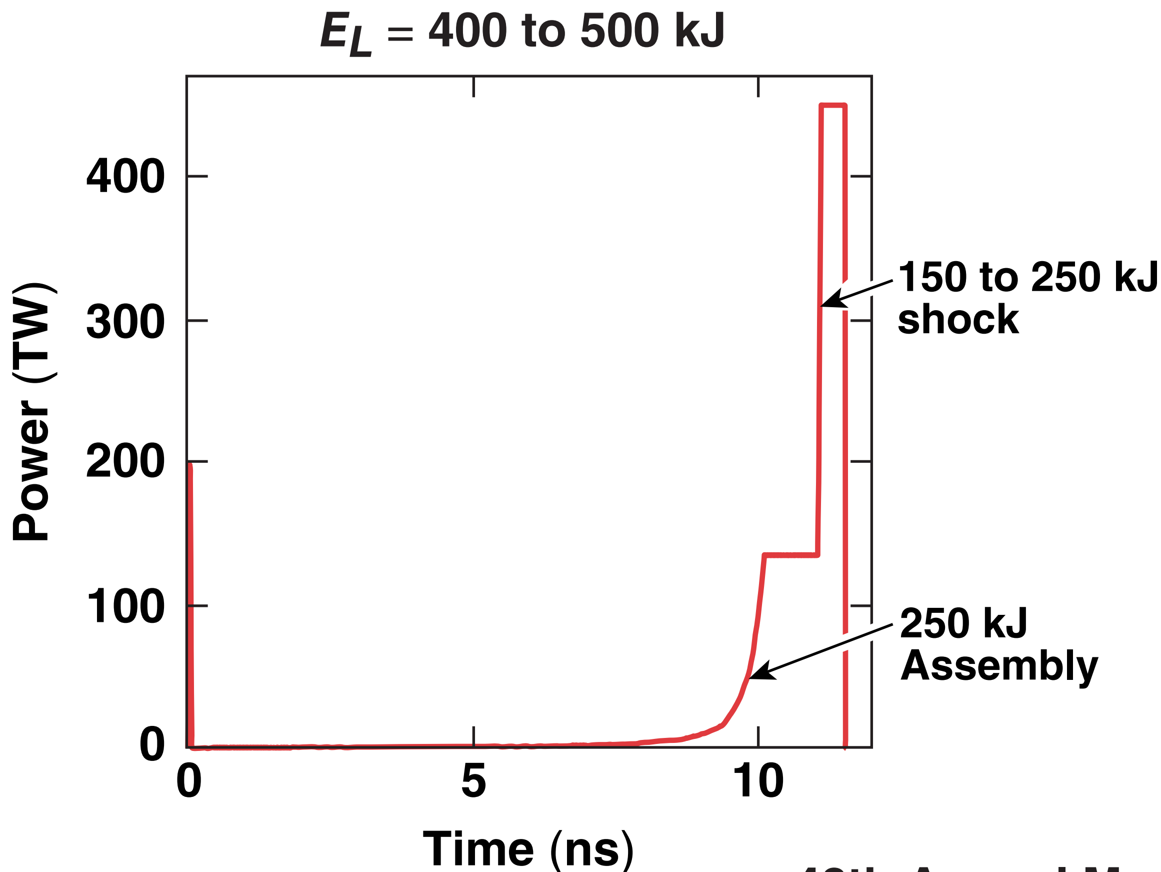
Shock Ignition of Thermonuclear Fuel with High-Areal Density



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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.

TC7632

Collaborators

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

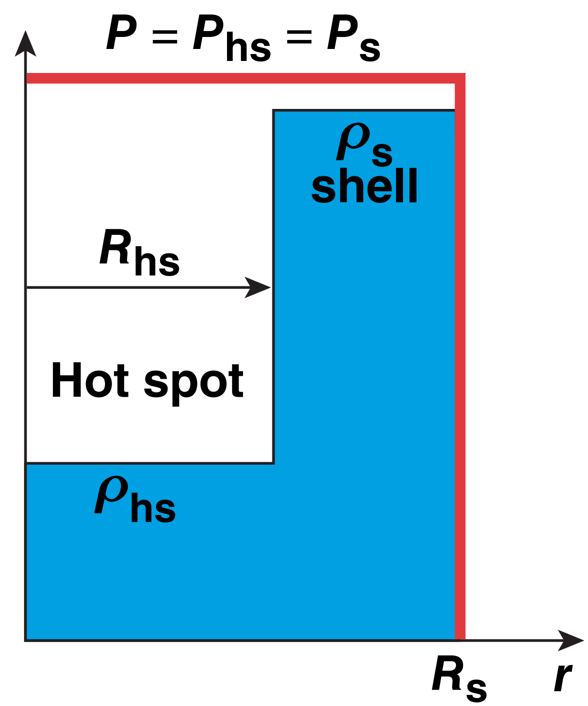
$$G = \frac{E_{fusion}}{E_{laser}} \sim \frac{\theta}{V_i^{1.2}}$$

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

- Higher $\rho R \rightarrow$ longer burn time
- Lower $V_i \rightarrow$ 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



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

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

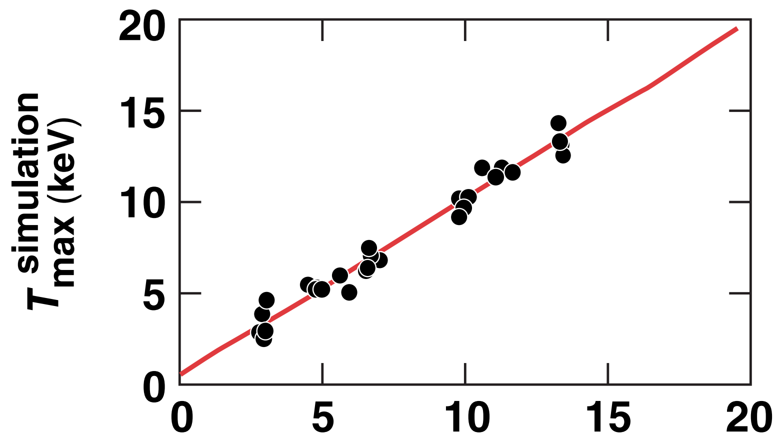
$$(\rho_s \Delta_s)^2 V^2 \left(T_{keV}^{isob} - 4.4\right) > const$$

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

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

For $V >> V_{min}$

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



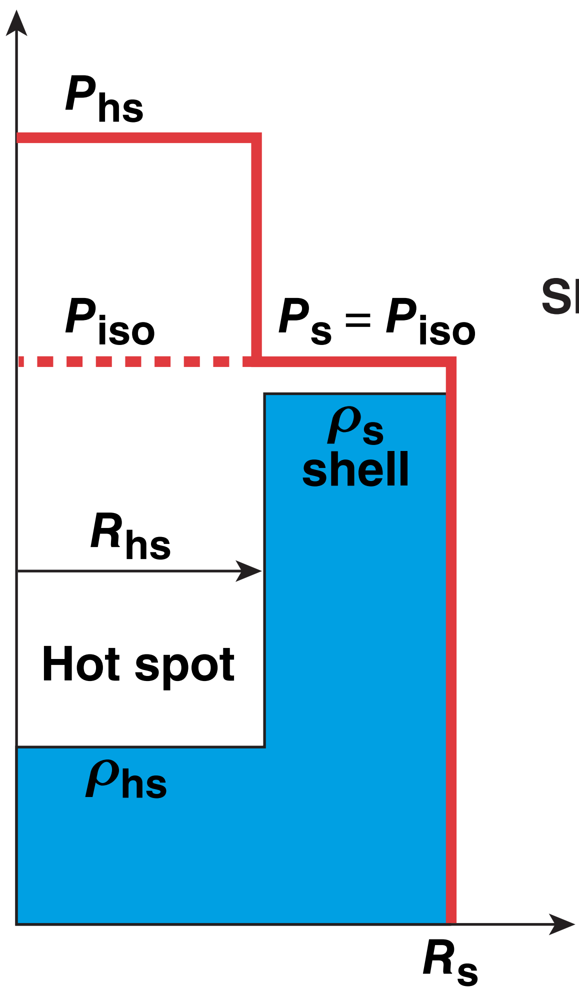
$$T_{hot\ spot}^{max}(keV)^{fit} = 7\left[\frac{V_i\,(cm/s)}{3 \times 10^7}\right]^{1.4}$$

Ignition requirements set a threshold for the shell areal density.

TC7596

C. Zhou, BO3.00003

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



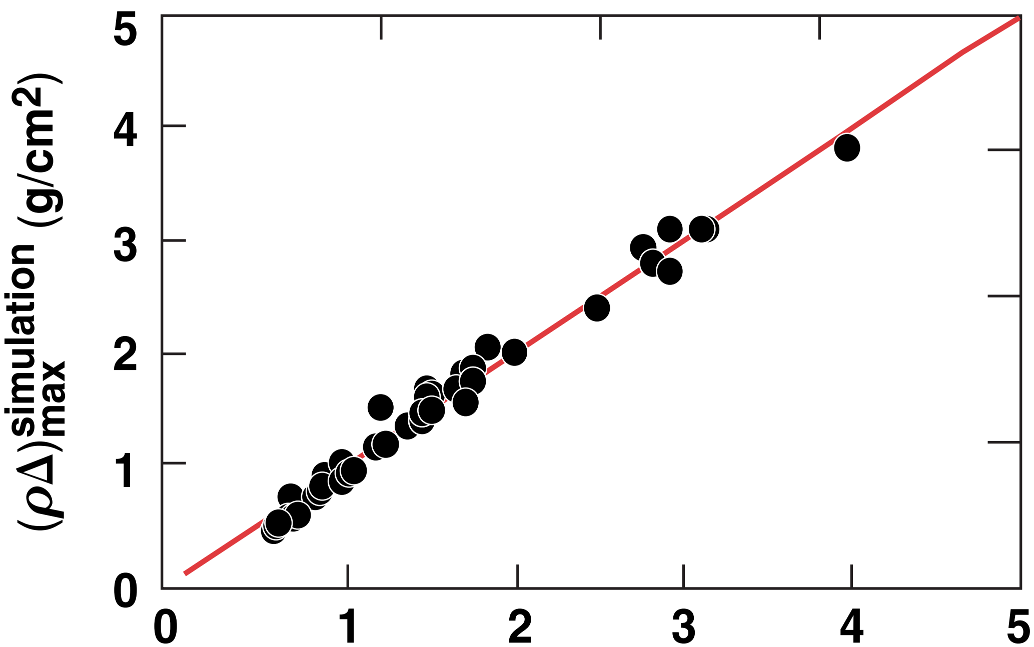
$$\hat{\phi}\left(\rho_s \Delta_s\right)^2_{iso} \quad V^2\left(\hat{\phi}^{0.3}\left(\frac{V}{V_{min}}\right)^{1.4} - 1\right) > \text{const}$$

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



$$(\rho\Delta)_{max}^{fit} = \frac{1.2}{\alpha^{0.57}}\left(\frac{E_L\,(\text{kJ})}{100}\right)^{0.33}\left(\frac{V\,(\text{cm/s})}{3\times 10^7}\right)^{0.1}\ \text{g/cm}^2$$

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

TC7598

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 $\hat{\phi} = 1$, $E^{non\text{-}isob} = 0$

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

For adiabatic compression of the hot spot

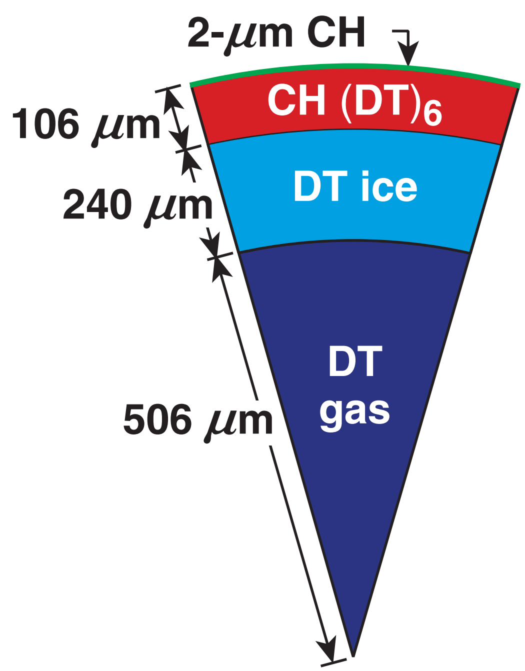
Large improvements for small reductions of the hot-spot radius.

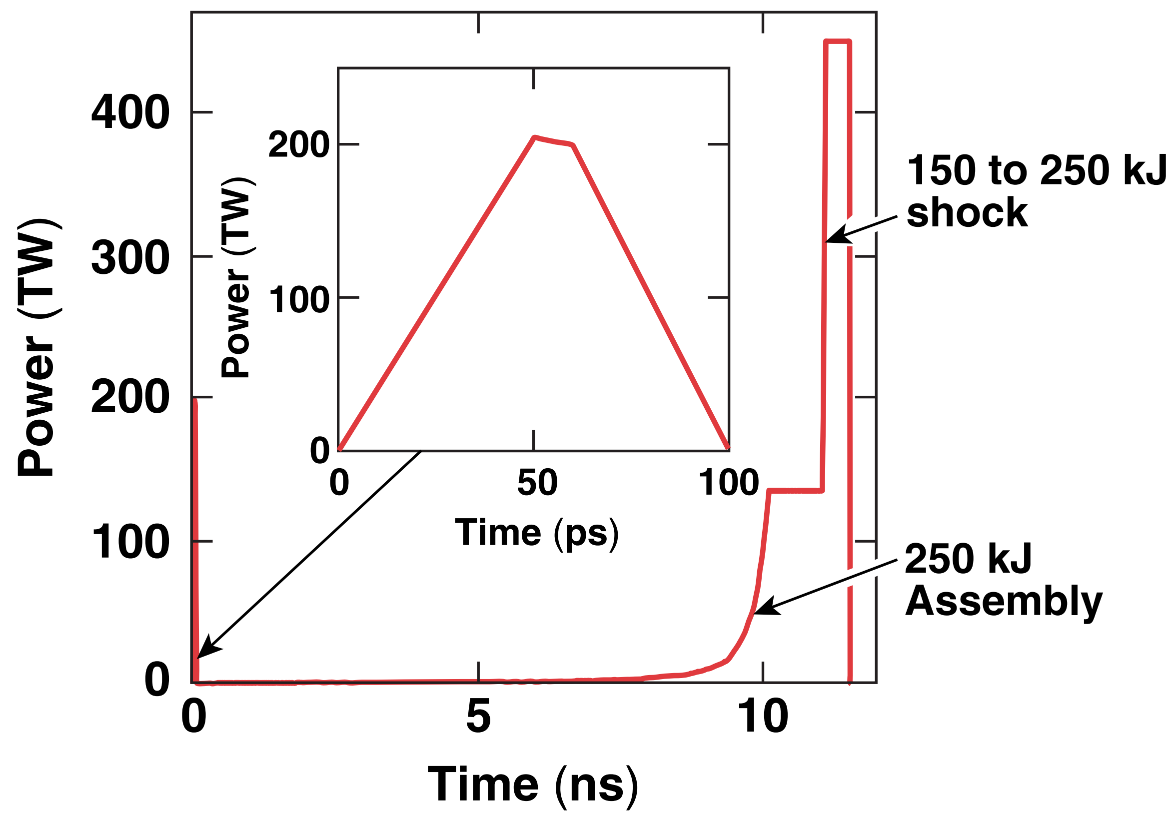
TC7599

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



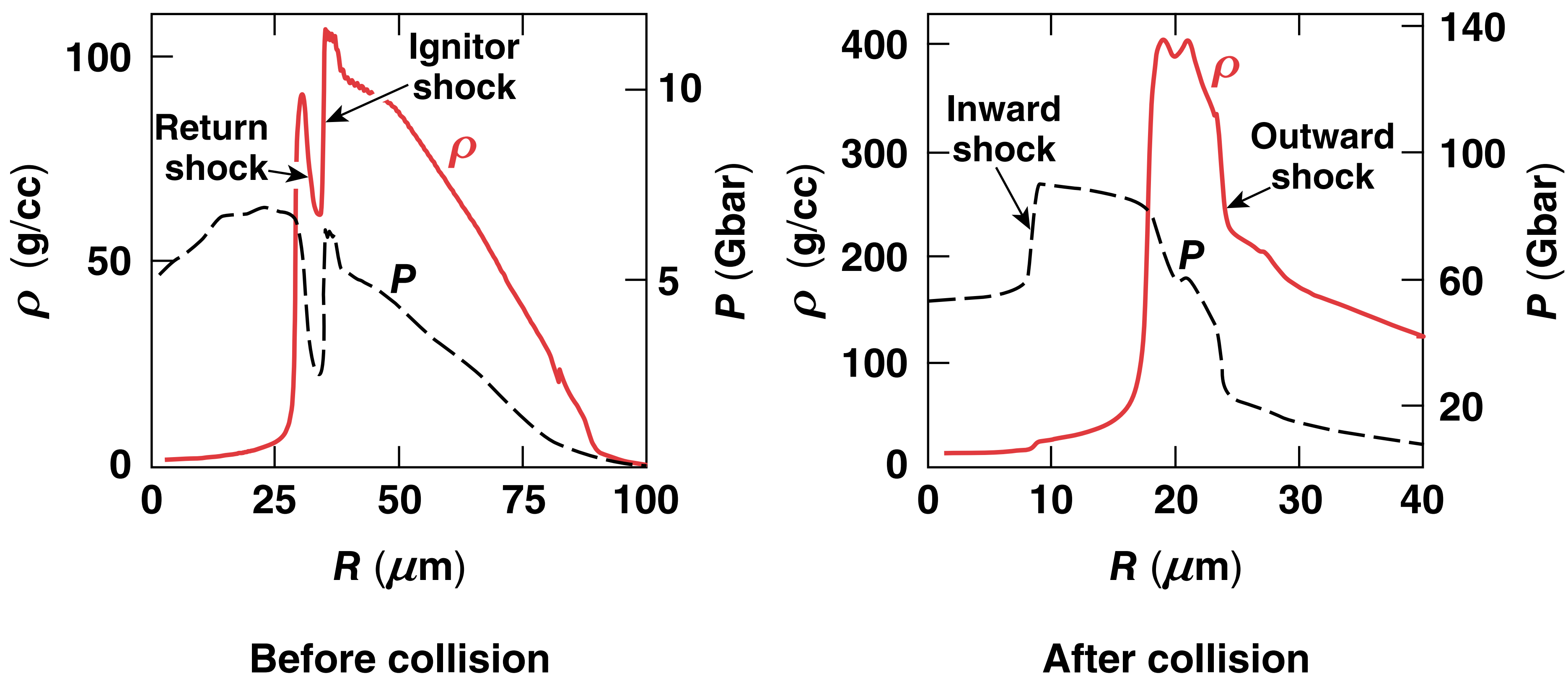


IFAR ≈ 18

Minimum shock energy for ignition = 50 kJ

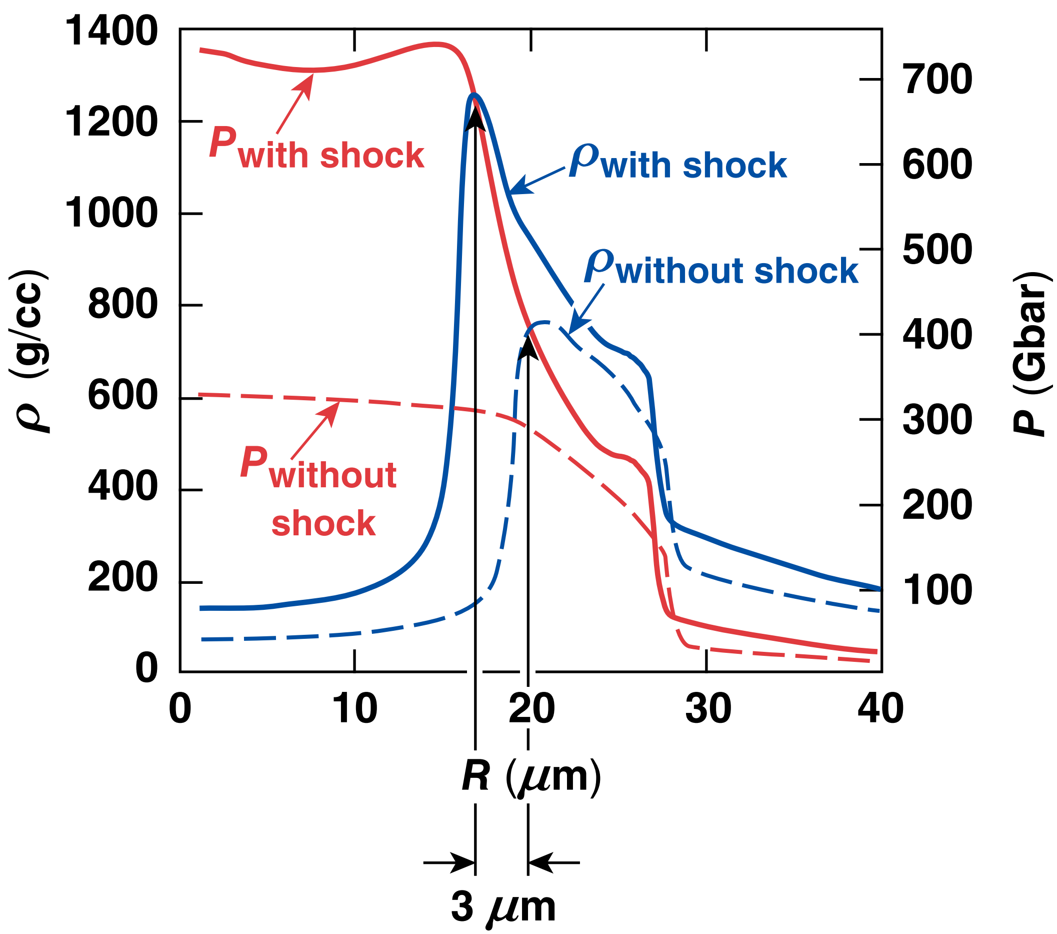
TC7600

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



TC7601

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



The shock compression is adiabatic

340 20

$$P_{shock} = P_{no\ shock}\left(\frac{R_{no\ shock}}{R_{shock}}\right)^5$$

17

P_{shock} = 720 Gbar

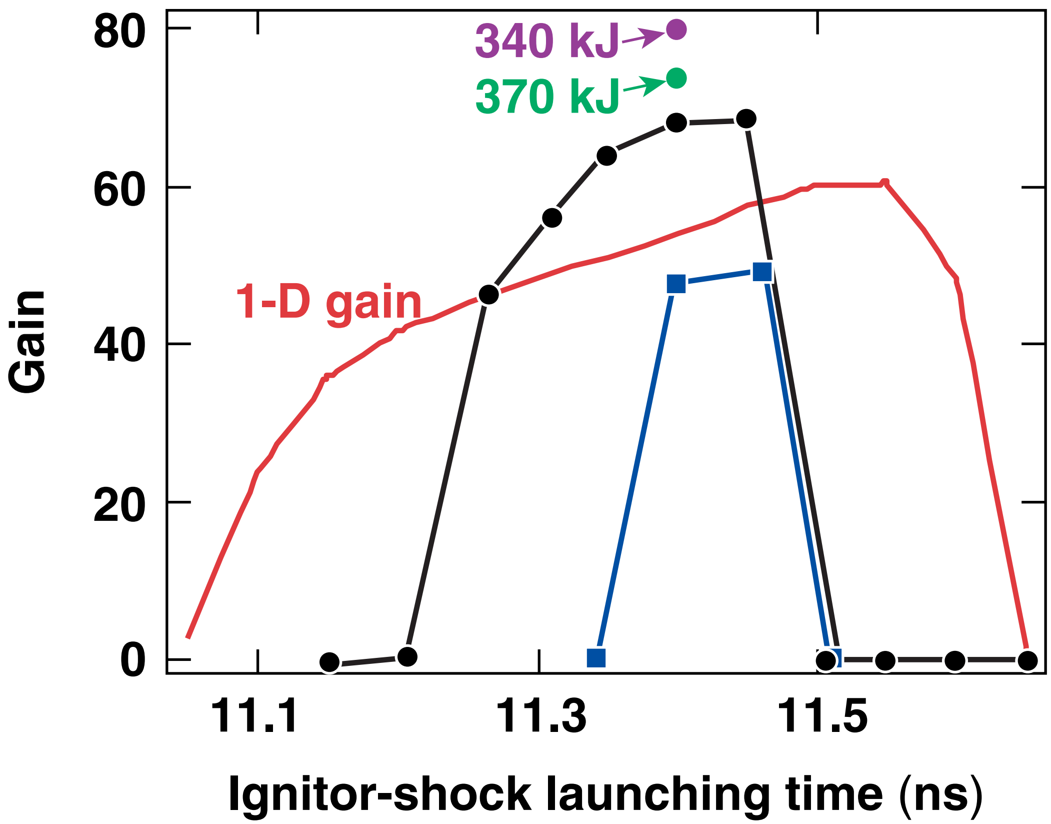
Non-isobaric enhancement

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

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

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

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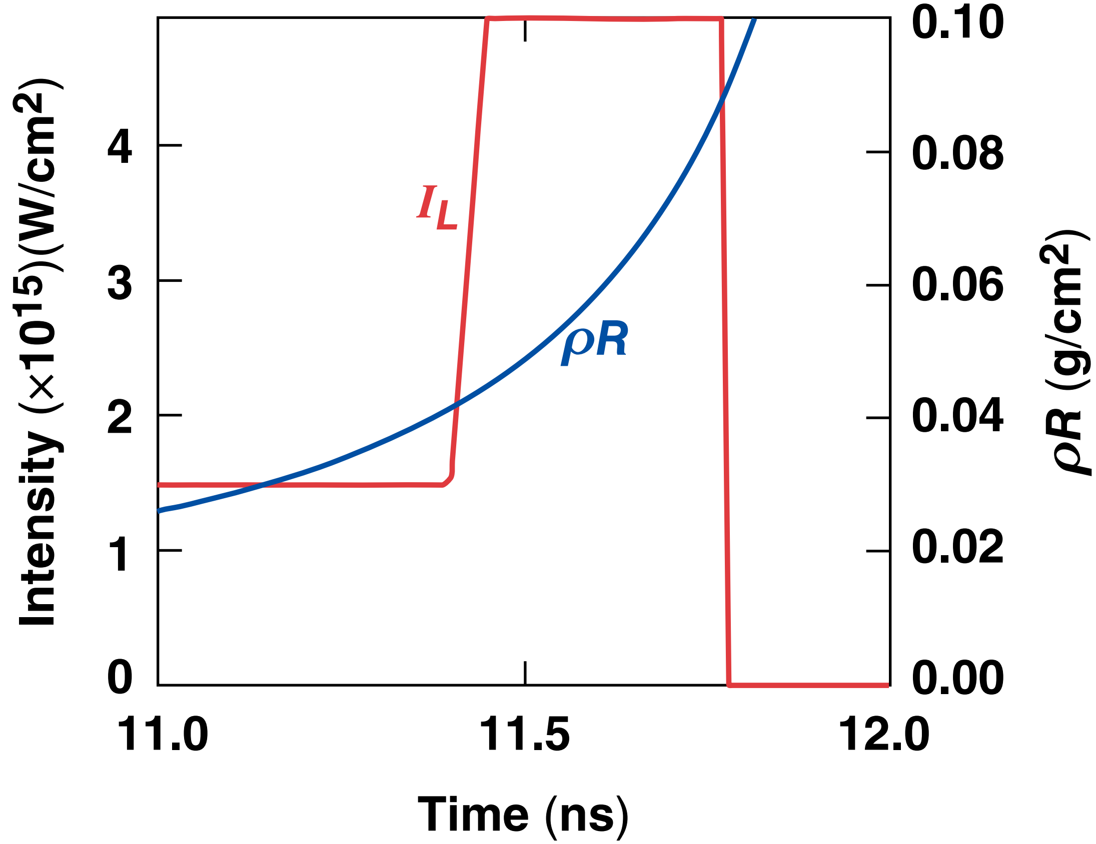
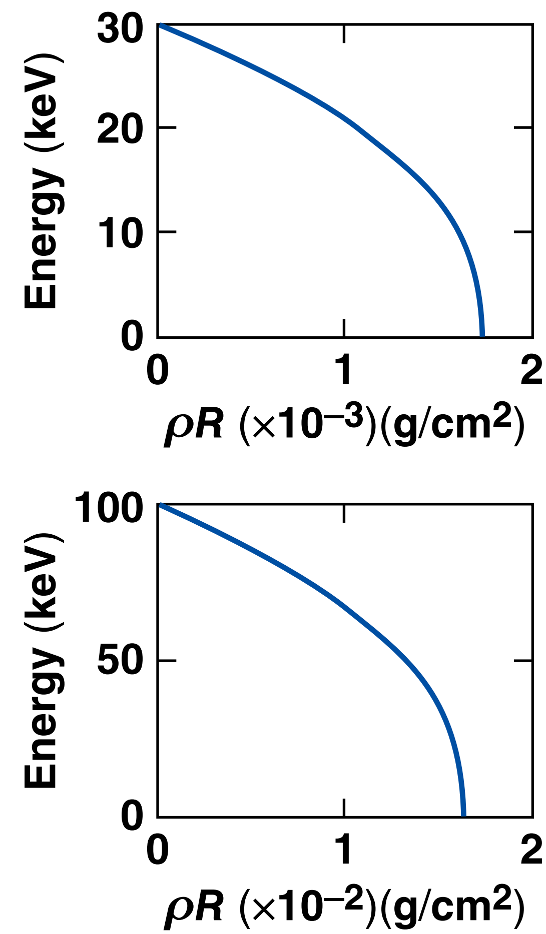
Hot electrons with energies <100 keV slow down on the shell's outer surface



Electron penetration



TC7605