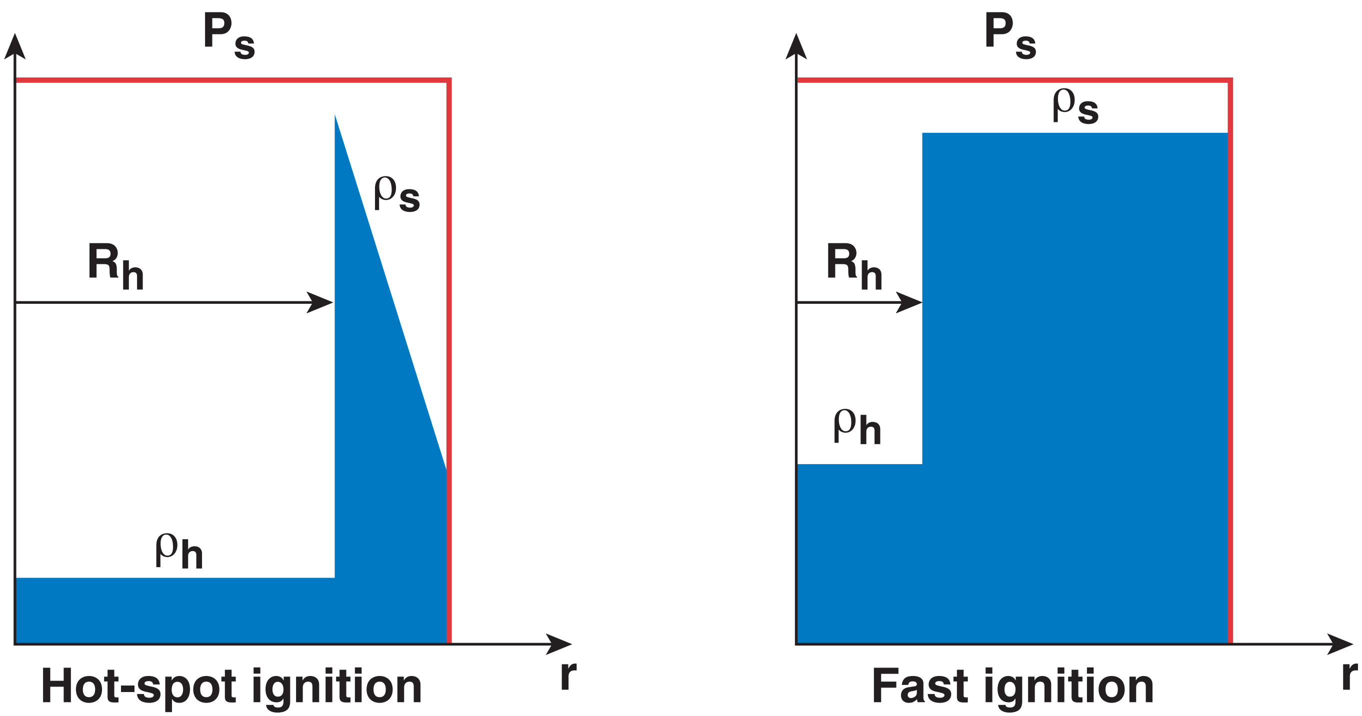
Fuel Assembly for Fast Ignition



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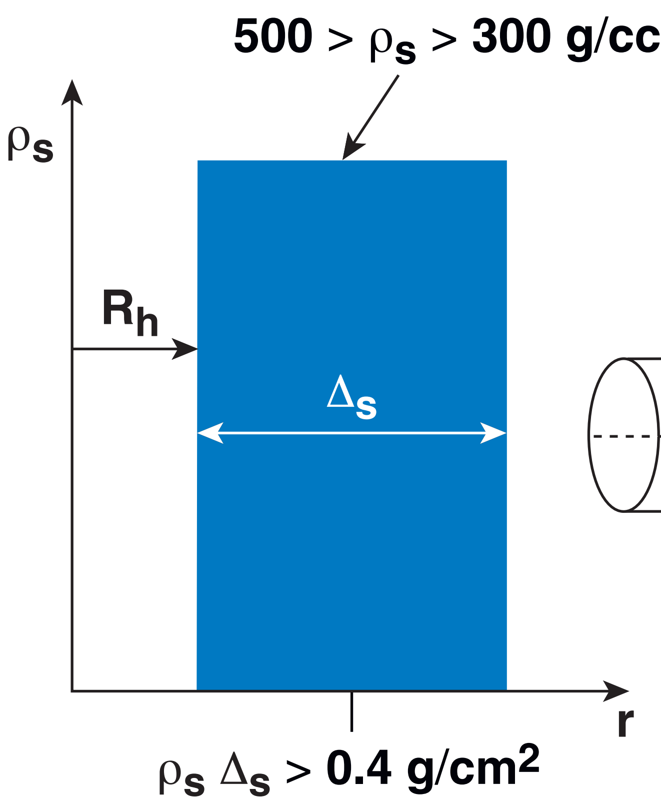
Summary

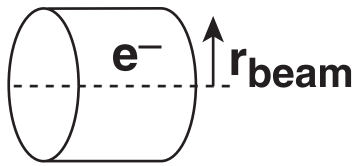
Significant progress has been made in the design of the fuel assembly for fast ignition using low-adiabat low-velocity implosions

- A high-yield fuel assembly has been designed; it requires a 750-kJ driver to produce
  - $\rho R \simeq 3$ g/cm^2
  - $300 < \rho < 500$ g/cc
  - hot-spot volume/total volume ~5% to 7%
  - estimated yield ~120 MJ (if ignited)
- A 25-kJ capsule can be assembled on the OMEGA laser to achieve
  - $\rho R \simeq 0.8$ g/cm^2, $300 < \rho < 500$ g/cc
  - hot-spot volume/total volume <15%
- Planned plastic–shell implosion experiments on OMEGA are expected to achieve $\rho R \simeq 0.3$–0.5 g/cm^2 and $\rho \simeq 200$–300 g/cc.

TC7084a

Ignition with fast ignition requires a fuel assembly with densities of 500 > ρ > 300 g/cc, ρR > 0.4 g/cm^2 and small hot-spot volume





$$E_{ig}\,(\text{kJ}) = 11\left[\frac{400}{\rho\,(\text{g/cc})}\right]^{1.85}$$

$$r_{beam}\,(\mu\text{m}) = 15\left[\frac{400}{\rho\,(\text{g/cc})}\right]^{0.95}$$

1 MeV e-stopping $\rho_s \Delta_s > 0.4$ g/cm^2

S. Atzeni, Phys. Plasmas 6, 3316 (1999).
C. K. Li and R. D. Petrasso, Phys. Rev. E. 70, 067401 (2004).

TC7068

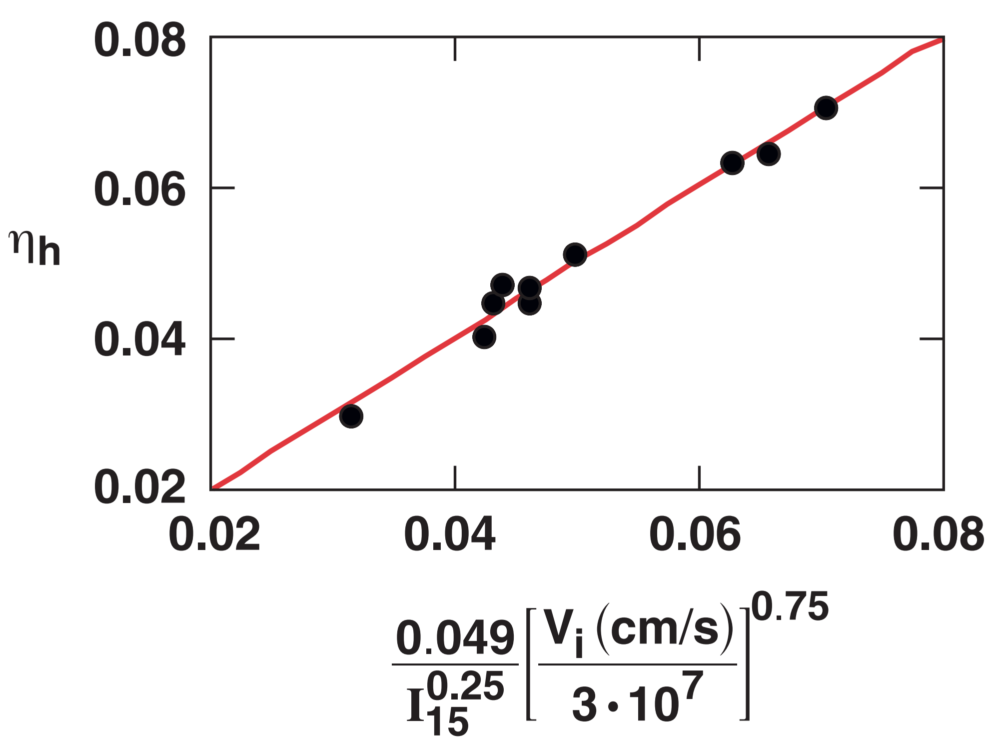
High yields with fast ignition require ρ > 300 g/cc, ρR ~3 g/cm^2, small hot-spot volume, and gains > 100

UR LLE

$$\text{Gain} = \frac{\eta_h}{V_i^2}\frac{\theta E_f}{m_{ion}}$$

Fraction burned $\rightarrow \theta \approx \dfrac{1}{1 + 7/\rho R}$

Hydro-efficiency $\rightarrow \eta_h = \dfrac{E_{kinetic}}{E_{Laser}}$



$$\text{Gain} = \frac{73}{I_{15}^{0.25}}\left(\frac{3 \cdot 10^7}{V_i}\right)^{1.25}\left(\frac{\theta}{0.2}\right)$$

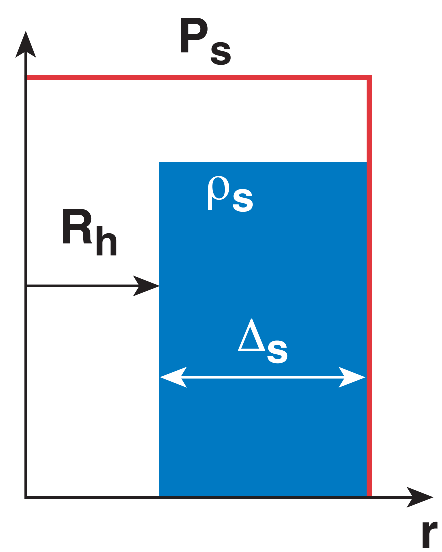
TC7069

Scaling laws relating stagnation to in-flight hydro-variables are derived from conservation equations

(1) Mass $\rightarrow$ $\rho_s \Delta_s \sim \frac{M_{sh}}{R_h^2 \Sigma(A_s)} \sim \frac{E_K}{R_h^2 V_i^2 \Sigma(A_s)}$

(2) Energy $\rightarrow$ $E_K \sim P_s (R_h + \Delta_s)^3$

(3) Entropy $\rightarrow$ $\alpha_s \sim \alpha_{if} \mathrm{Mach}_{if}^{2/3}$



$A_s \equiv R_h/\Delta_s$ $\leftarrow$ Stagnation aspect ratio

$\Sigma(x) \equiv 1 + 1/x + 1/(3x^2)$ $\leftarrow$ Volume factor

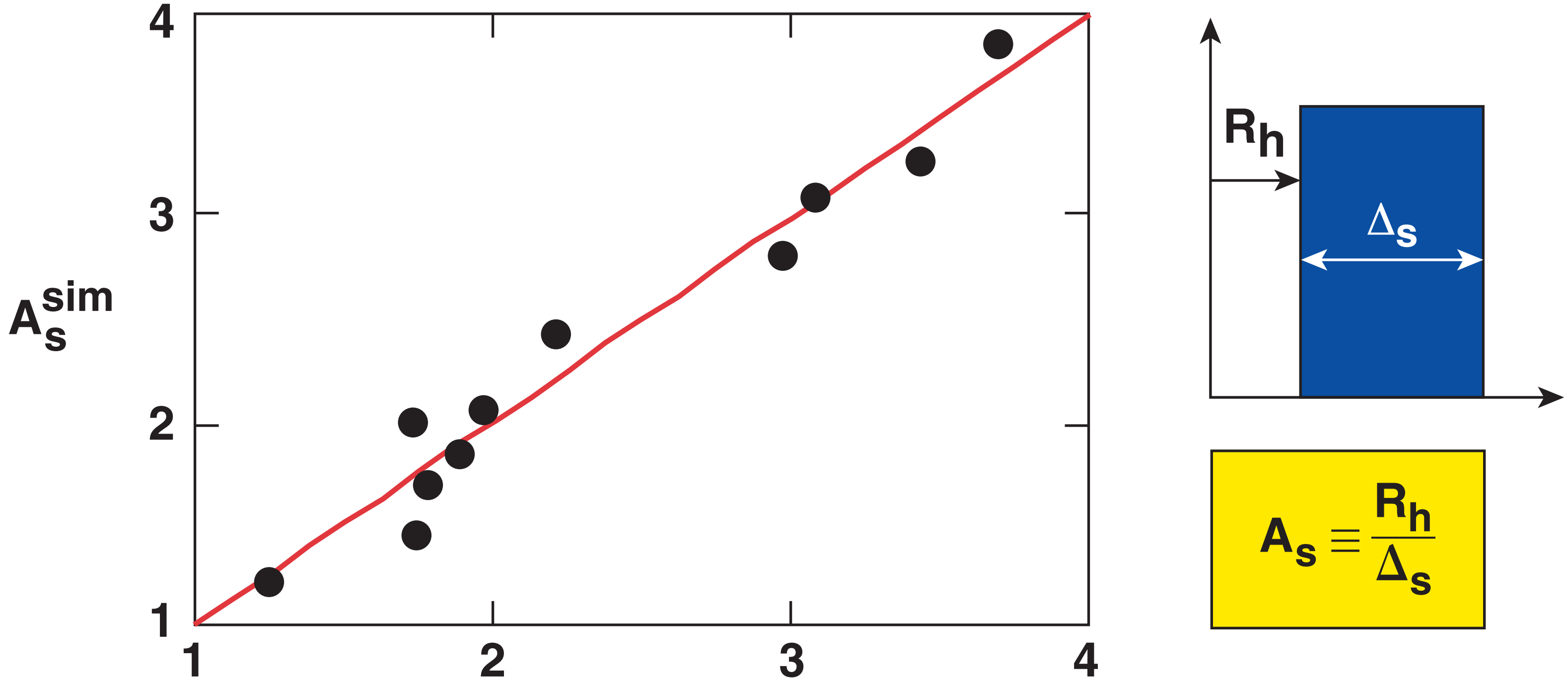
$\alpha_{if} \equiv$ in-flight adiabat

Unknowns $\rightarrow$ P_s, ρ_s, A_s, Δ_s

TC7080

R. Betti and C. Zhou, Phys. Plasmas (in press).

Simulations of optimized implosions (max ρR and ρ) yield a scaling relation for the stagnation aspect ratio

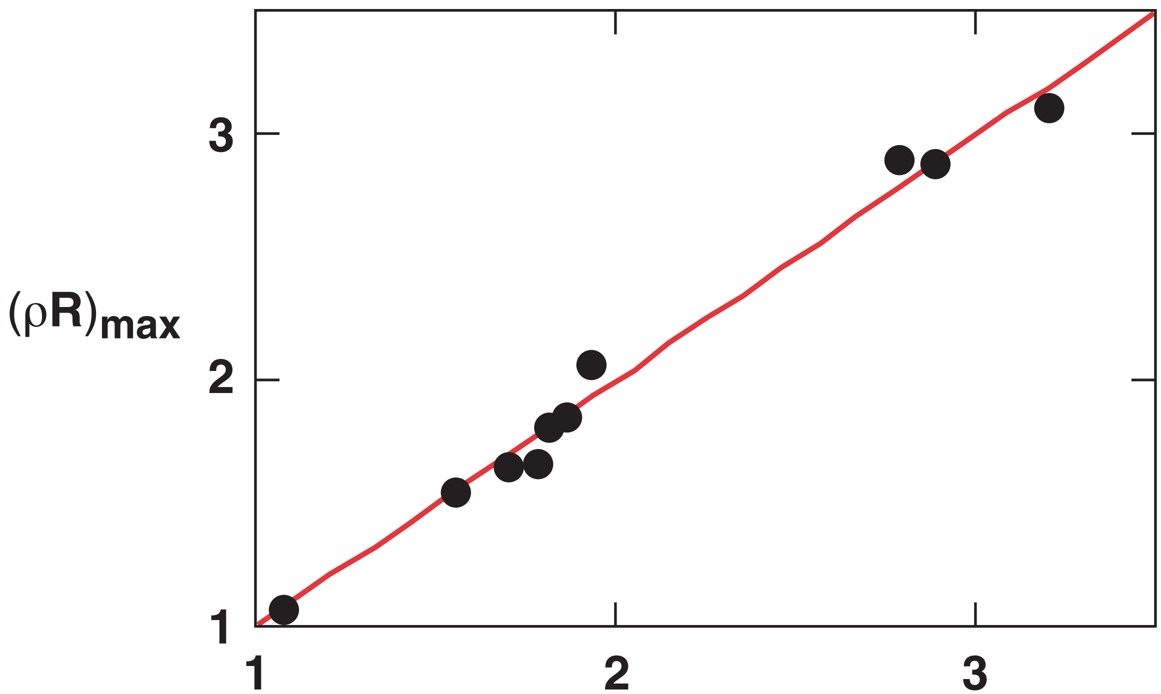


$$A_s^{fit} = 2.1\left[\frac{V_i\,(\text{cm/s})}{3 \cdot 10^7}\right]^{0.96}$$

TC7017

The areal density is weakly dependent on velocity; it increases for lower adiabats and greater energies

$$(\rho_s \Delta_s)^{\text{theory}} \sim E_L^{0.33} V_i^{0.03} \alpha_{if}^{-0.8}$$

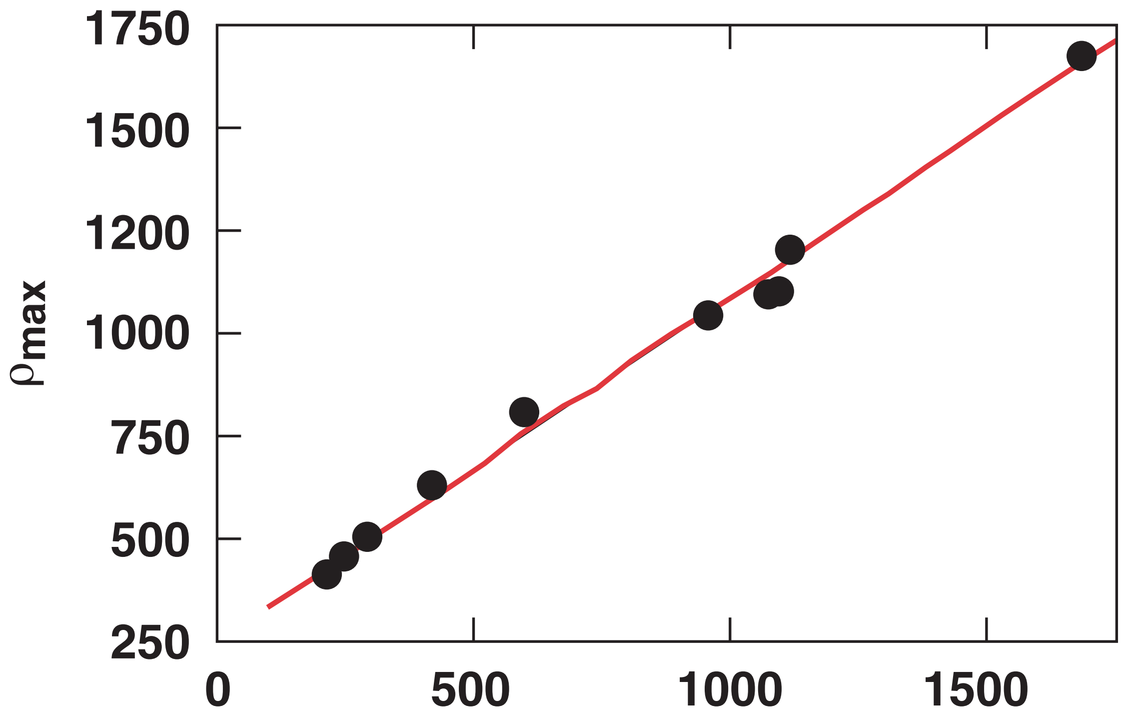


$$(\rho R)_{max}^{fit} = \frac{1.3}{\alpha_{if}^{0.55}} \left[\frac{E_L\ (\text{kJ})}{100}\right]^{0.33} \left[\frac{V_i\ (\text{cm/s})}{3 \cdot 10^7}\right]^{0.06}$$

TC7070

The density is independent of energy; it increases with the velocity and decreases with the adiabat

$$\rho_s^{theory} \sim V_i^{1.4} I_L^{0.13} \alpha_{if}^{-1.2}$$



$$\rho_{max}^{fit} = \frac{792}{\alpha_{if}} I_{15}^{0.13} \left[\frac{V_i\,(cm/s)}{3 \cdot 10^7}\right]$$

TC7071

High-gain fuel assemblies for fast ignition can be designed using the scaling formulas

UR LLE

→ **Low adiabats enhance densities and areal densities: minimum practical adiabat $\alpha = 0.7$ to 0.8**

→ $\rho R(\alpha = 0.7) \approx 3 \Rightarrow E_{Laser} \approx 750$ **kJ**

→ $\rho_{max}(\alpha = 0.7) \approx 600$ **g/cc** $\Rightarrow V_i(\text{cm/s}) \approx 1.7 \cdot 10^7$ **cm/s**

→ $V_i \approx 1.7 \cdot 10^7$ **cm/s** $\Rightarrow R_h/\Delta_s \sim 1$

High-gain FI target: $E_L = 750$ kJ, $\alpha = 0.7$, $V_i \approx 1.7 \cdot 10^7$ cm/s

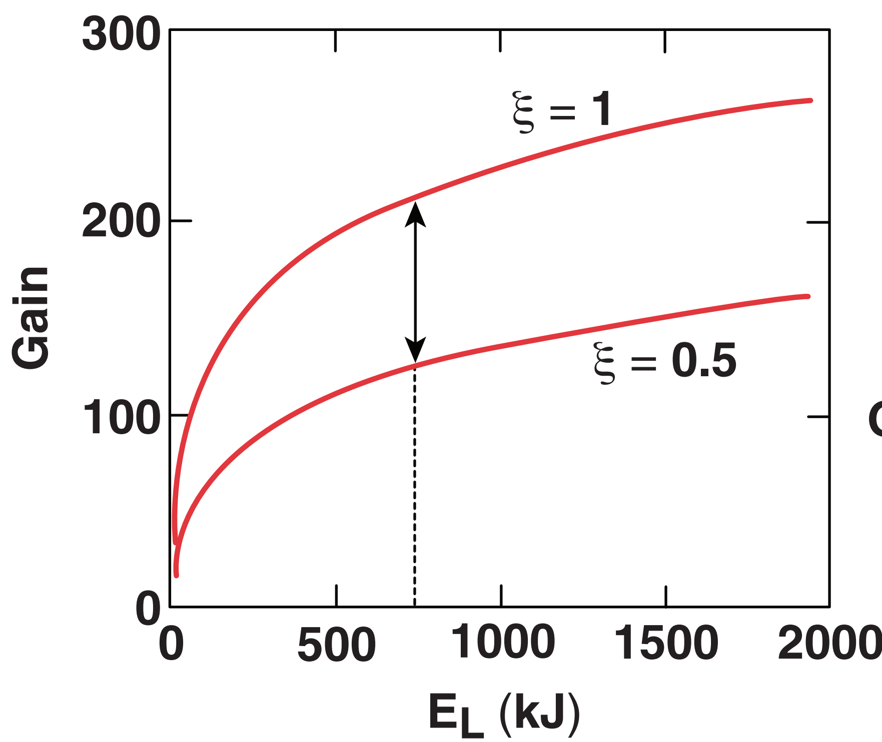
Estimated yield ~ 120 MJ

In-flight aspect ratio (IFAR) = 18

TC7072a

R. Betti and C. Zhou, Phys. Plasmas (in press).

For a fixed minimum adiabat and fixed peak density, the gain (without PW) depends only on the driver energy



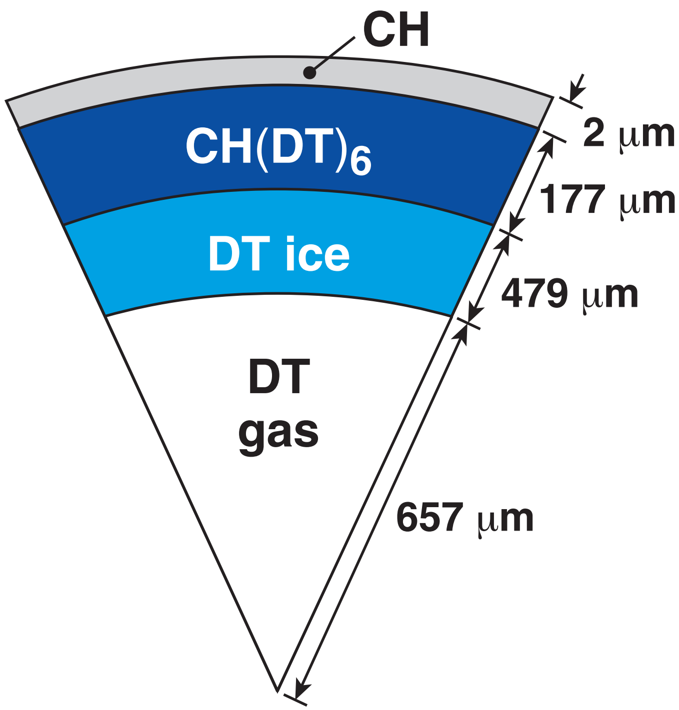
$$V_I\,(\mathrm{cm/s}) = \frac{1.7\times 10^7}{I_{15}^{0.13}}\left(\frac{\rho_{max}}{600}\right)\left(\frac{\alpha_{if}}{0.7}\right)$$

$$\mathrm{Gain}\begin{bmatrix}\rho_{max} & = & 600\\ \alpha_{if} & = & 0.7\\ I_{15} & = & 1\end{bmatrix} = \frac{742}{1 + 22/\xi E_L^{0.33}\,(\mathrm{kJ})}$$

ξ = fraction of $(\rho R)_{max}$ available for burn

TC7256

A high-yield target has been designed for a 750-kJ laser driver



Energy	Implosion velocity	α	IFAR
750 kJ	$1.7 \cdot 10^7$ cm/s	0.7	18

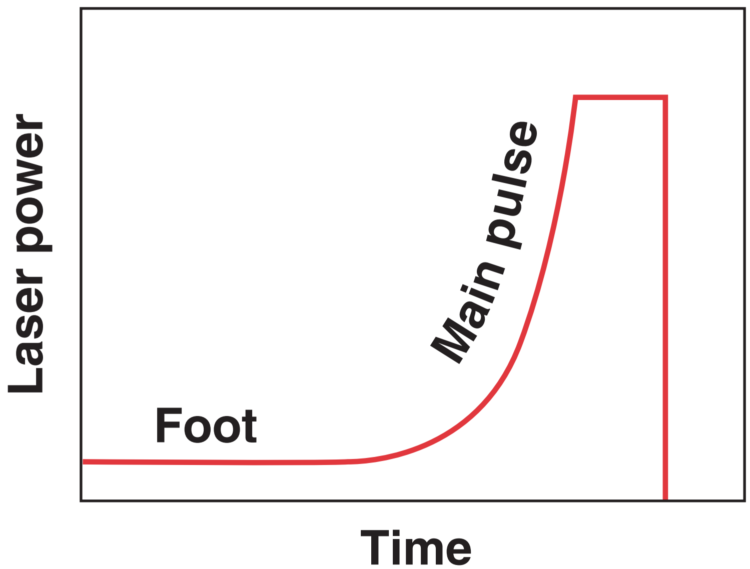
Maximum averaged density	Peak Density	Maximum ρR
550 g/cc	670 g/cc	3 g/cm^2

TC7018

Using the relaxation-type laser pulse leads to improved hydrostability and a lower laser–power contrast ratio

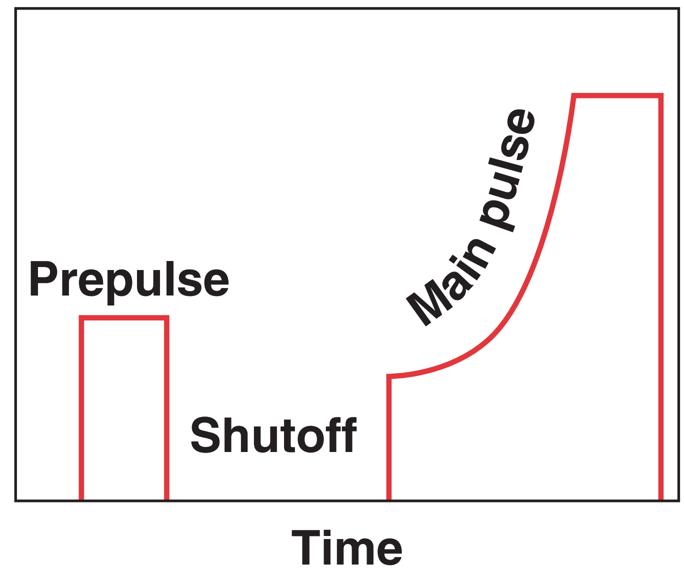
UR LLE

Standard flat-adiabat pulse



$P^{(Mb)}_{foot} \approx 2\,\alpha_{if}$

Relaxation shaped-adiabat pulse

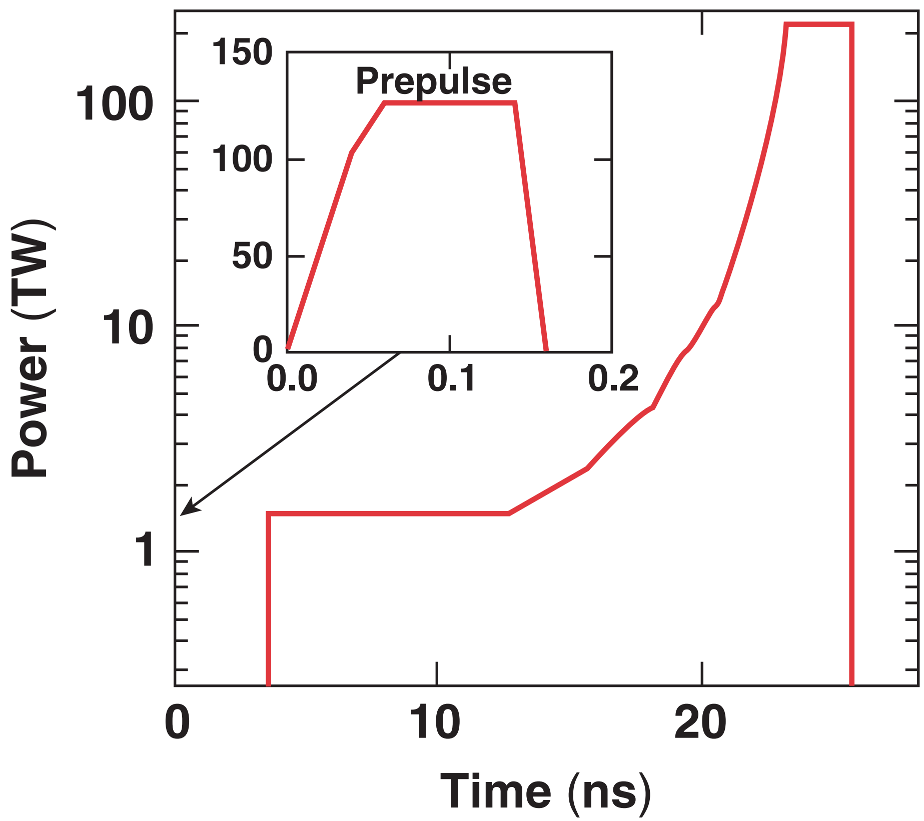


$P^{(Mb)}_{foot} \approx 6\,\alpha_{if}$

R. Betti *et al.*, Phys. Plasmas 12, 042703 (2005).

TC7081a

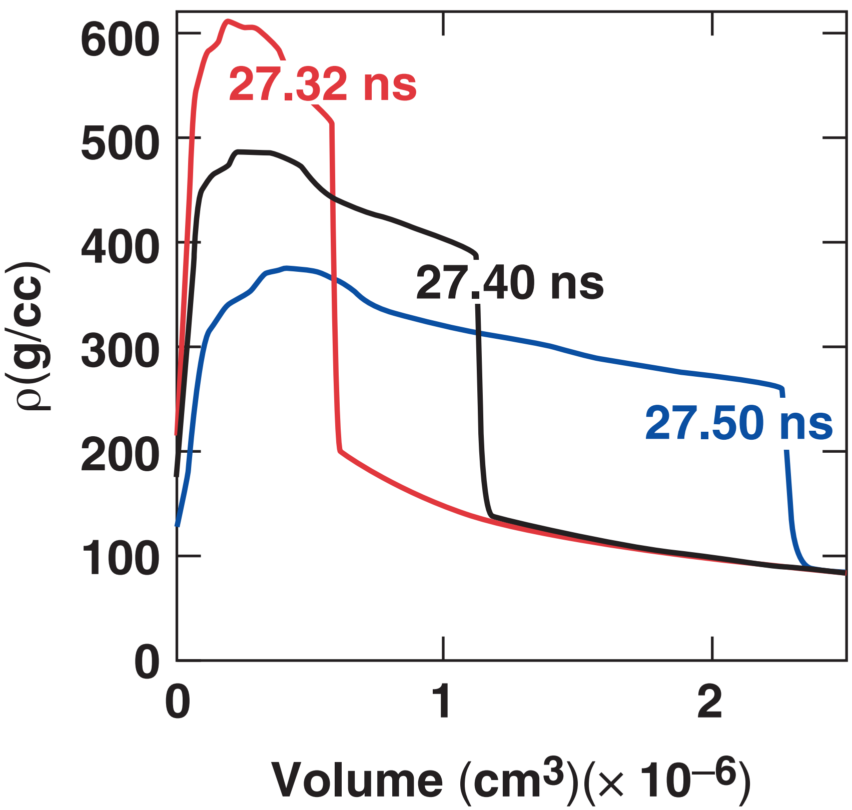
The 750-kJ capsule is driven by a relaxation laser pulse with a 22-ns main pulse and a contrast ratio of 150

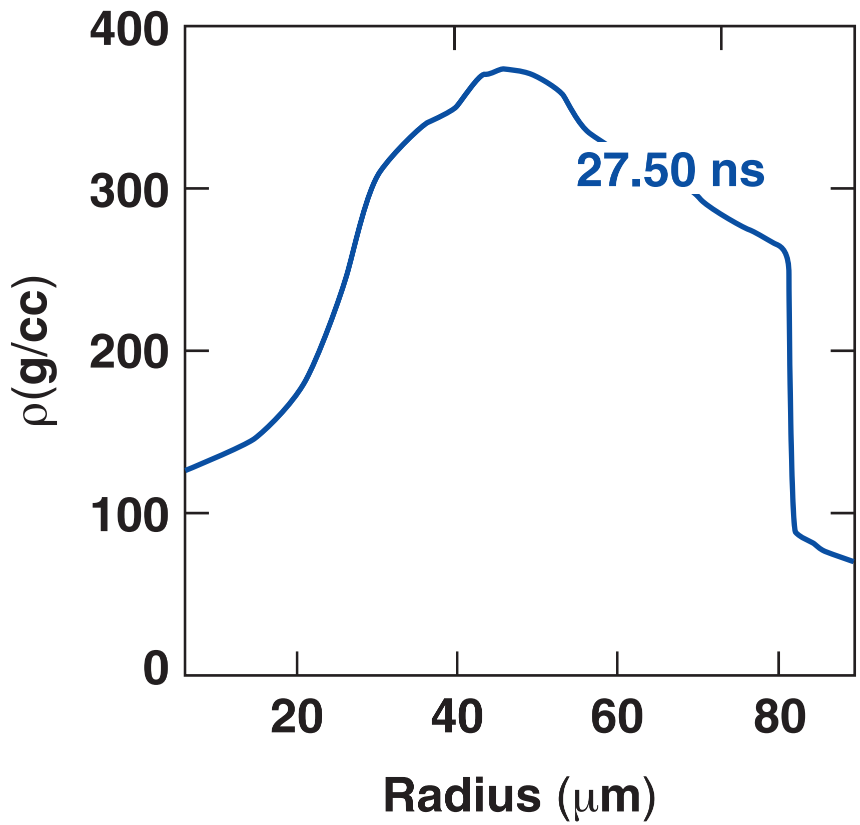


Can NIF assemble high-gain FI targets?
Indirect-drive pulse is 18 ns with a contrast ratio of ~100

TC7019

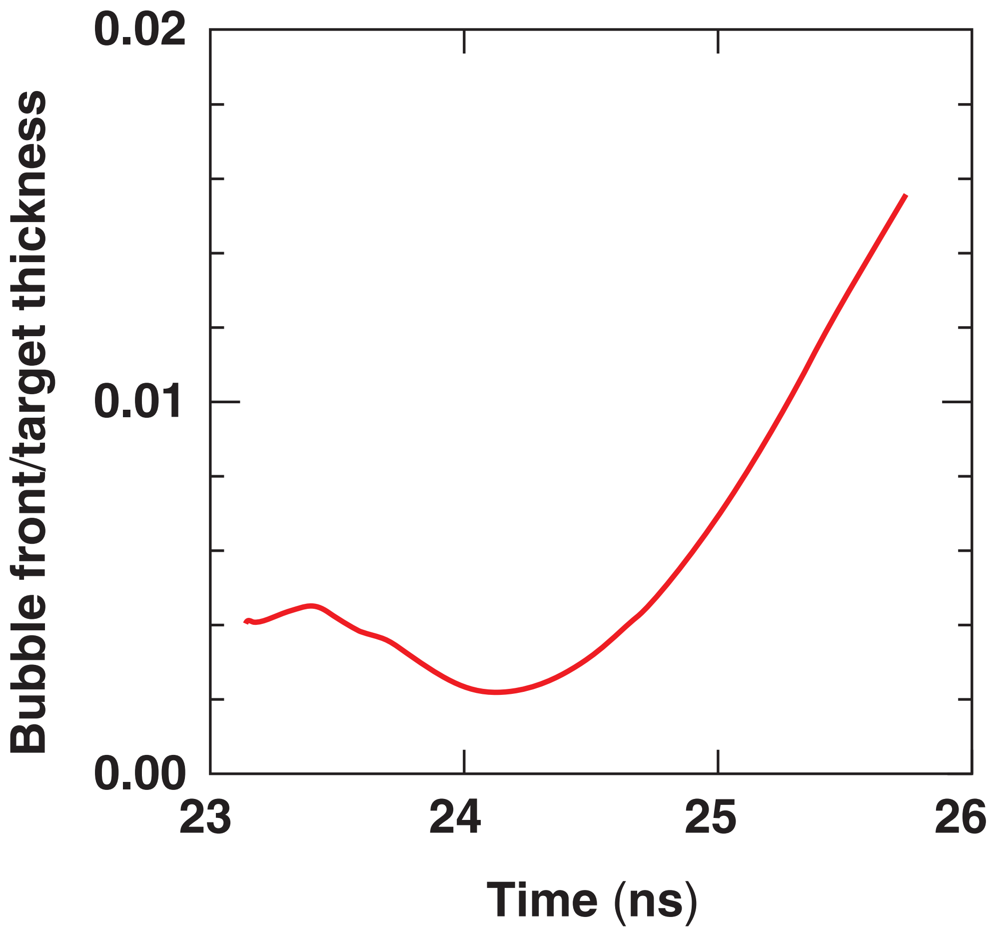
The 750-kJ capsule yields a hot-spot volume < 8% of the compressed volume and a quasi-isochoric density profile





TC7074

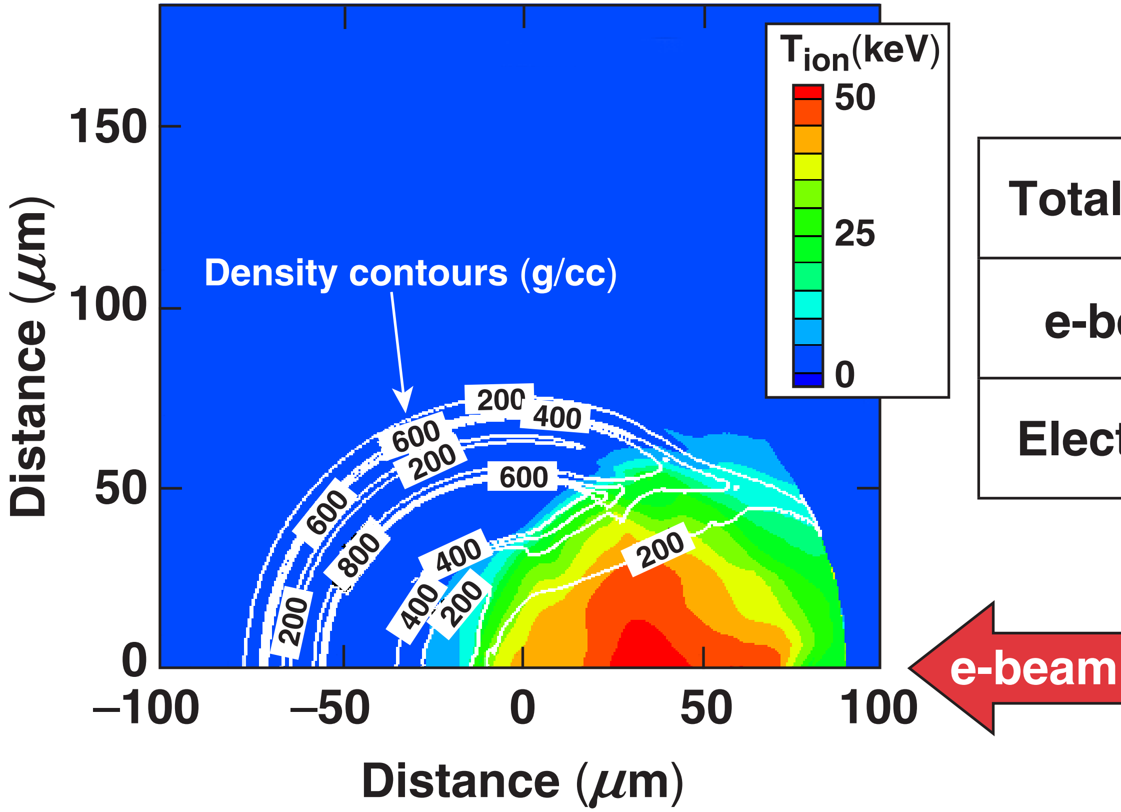
The slow implosion velocity leads to negligible Rayleigh–Taylor growth during the laser flat top



Results from RT postprocessor based on Haan–Goncharov models and NIF laser nonuniformities with 1-THz SSD.

V. N. Goncharov *et al*., Phys. Plasmas 7, 2062 (2000).
S. W. Haam, Phys. Rev. A 39, 5812 (1989).

2-D hydro-simulations of ignition and burn of the 750-kJ target show energy yields >100 MJ



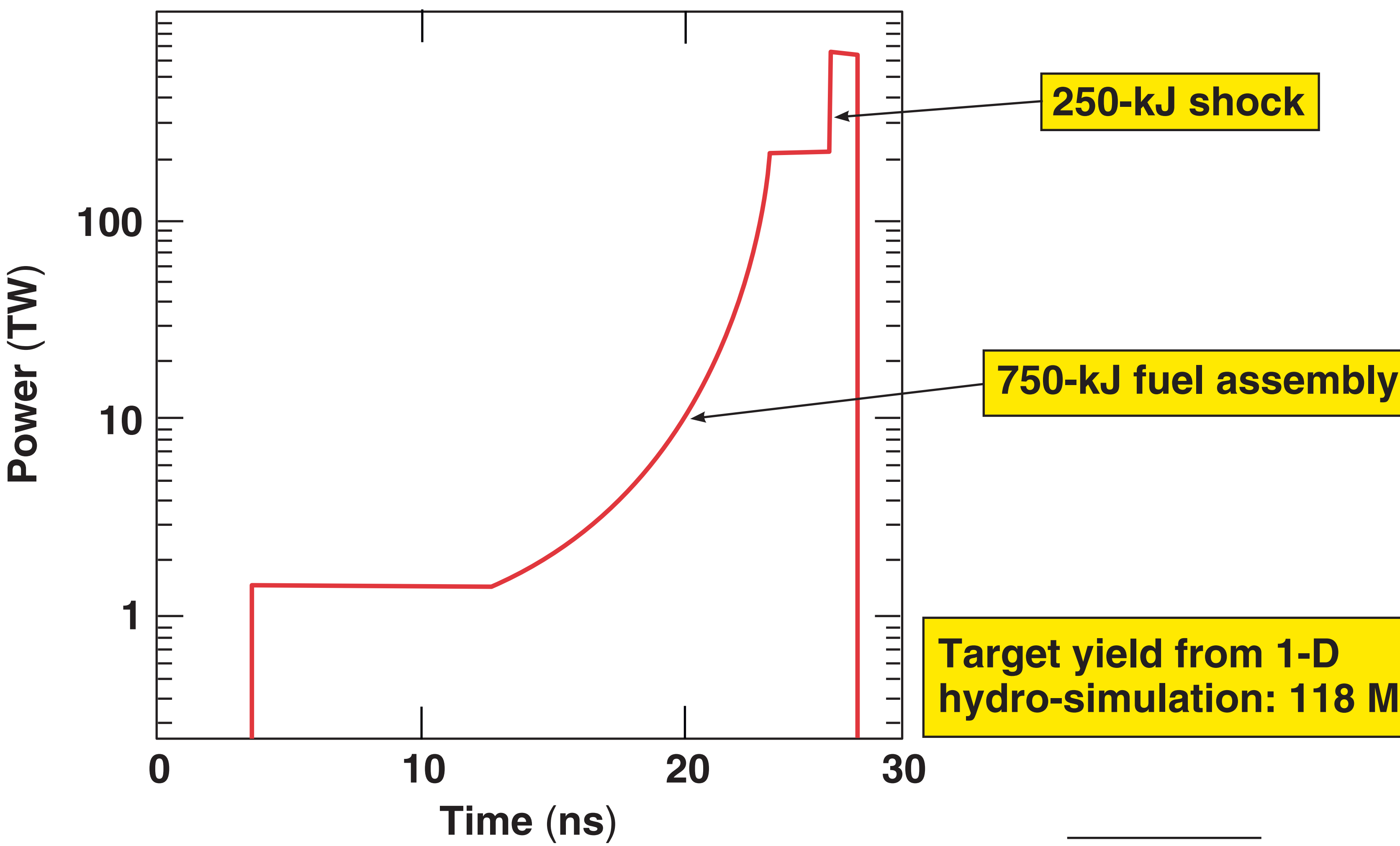
Total beam energy (kJ)	12–20
e-beam radius (μm)	20
Electron energy (MeV)	2–3

Energy yield ≈ 116 MJ

TC7282

*J. A. Delettrez, this conference

The relatively cold hot spot of such fuel assemblies can also be ignited by a spherically convergent shock*

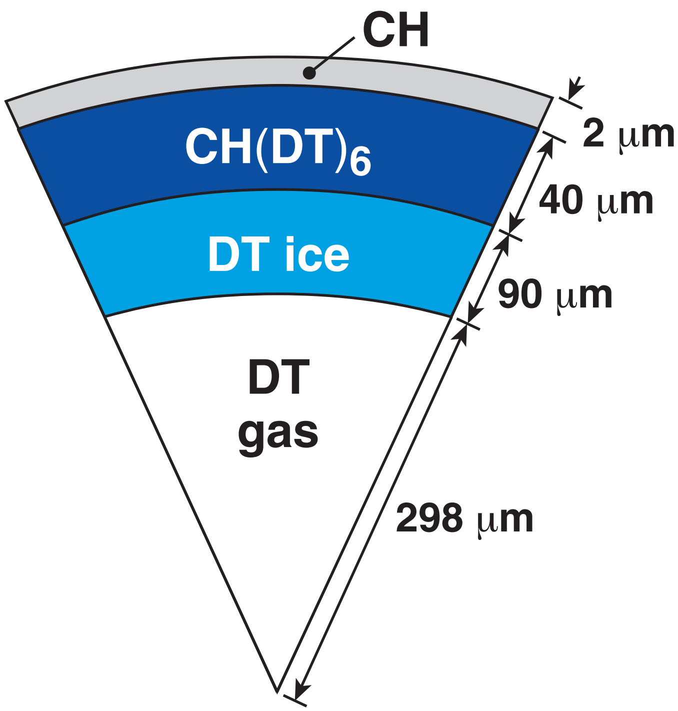


Target yield from 1-D hydro-simulation: 118 MJ

TC7257

*C. Zhou, this conference.

A 25-kJ driver can assemble fuel for fast ignition using low-adiabat implosions of thick shells with a pulse compatible with the OMEGA Laser System

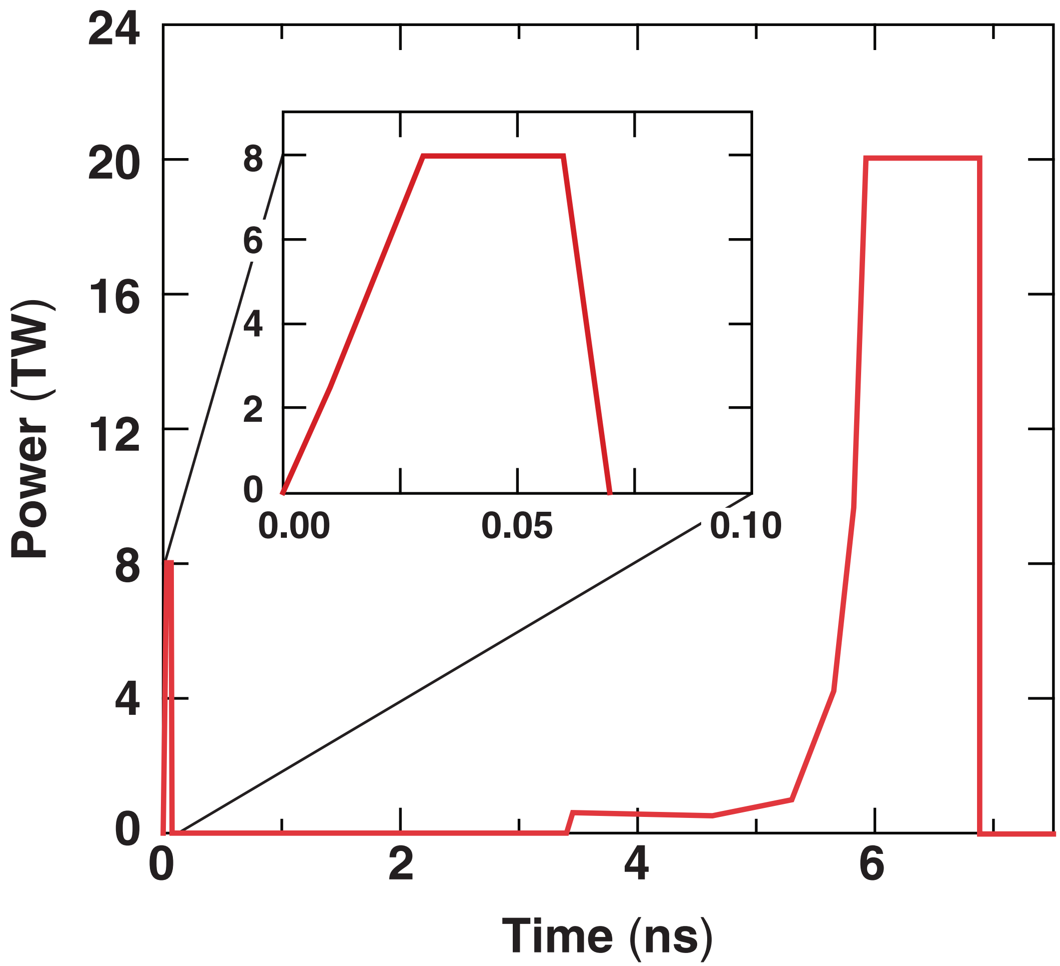


Energy	IFAR	α
25 kJ	30	1

Implosion velocity	Maximum density	Maximum ρR
$2.6 \cdot 10^7$ cm/s	700 g/cc	0.8 g/cm^2

TC7075a

The 130-μm capsule is driven by a relaxation laser pulse within the capabilities of the OMEGA laser



Main pulse length = 3.5 ns

Prepulse width = 70 ps

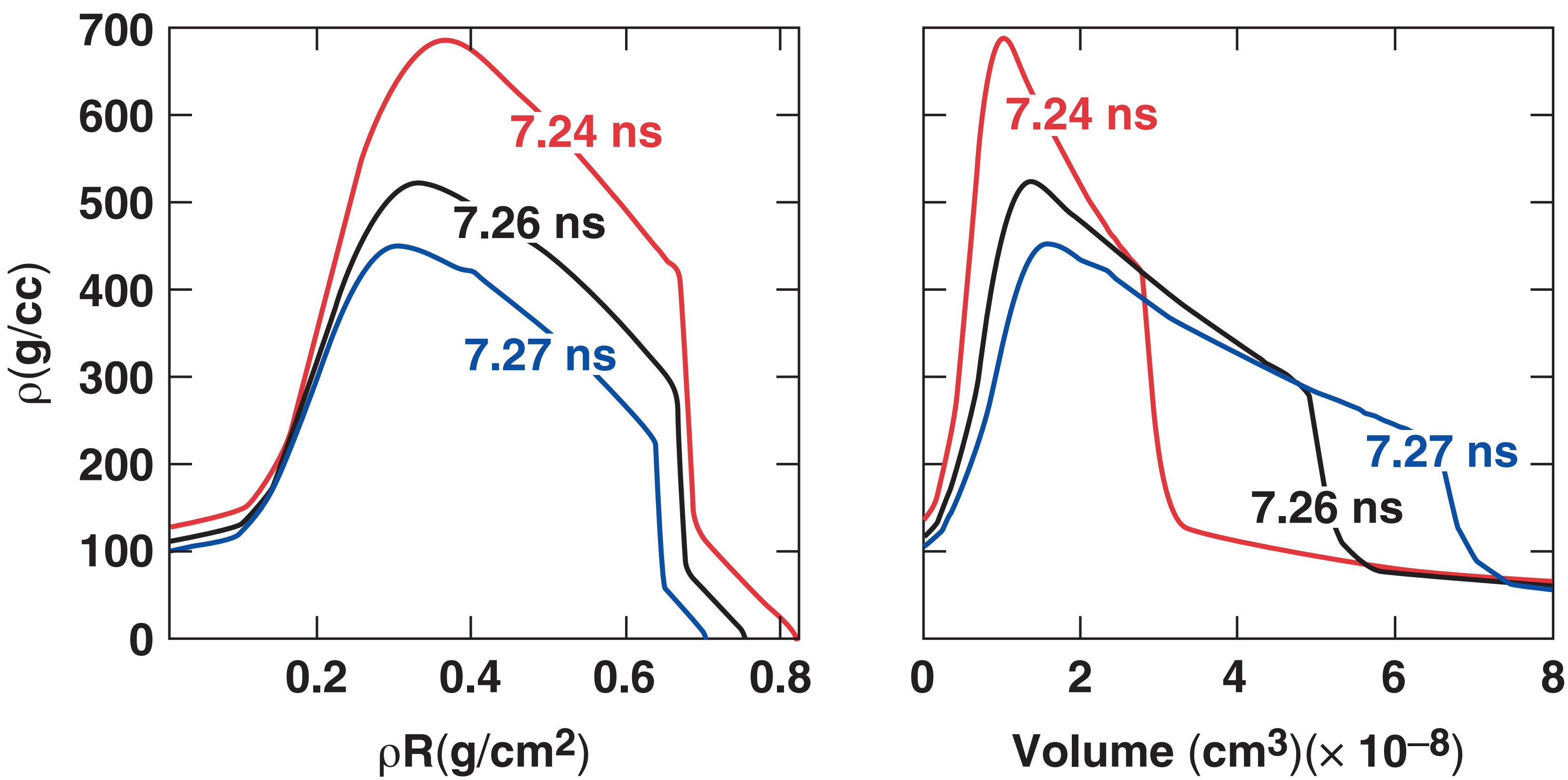
Prepulse/main = 0.4

Main contrast ratio = 32

Pulse energy = 25 kJ

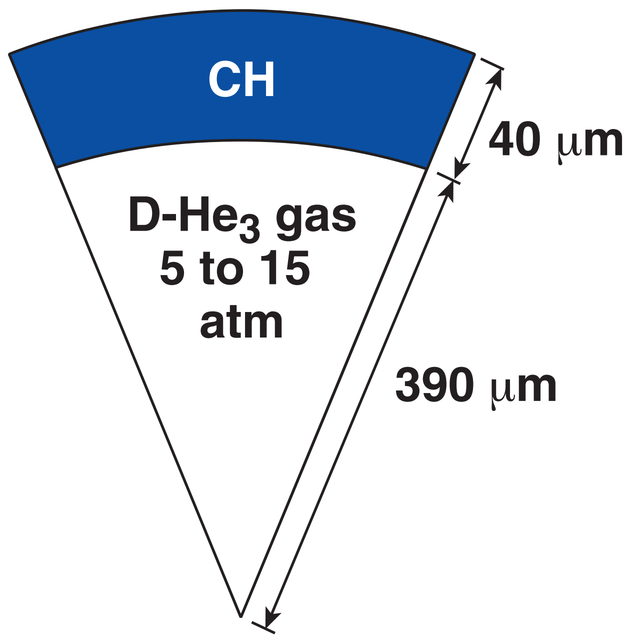
Peak power = 20 TW

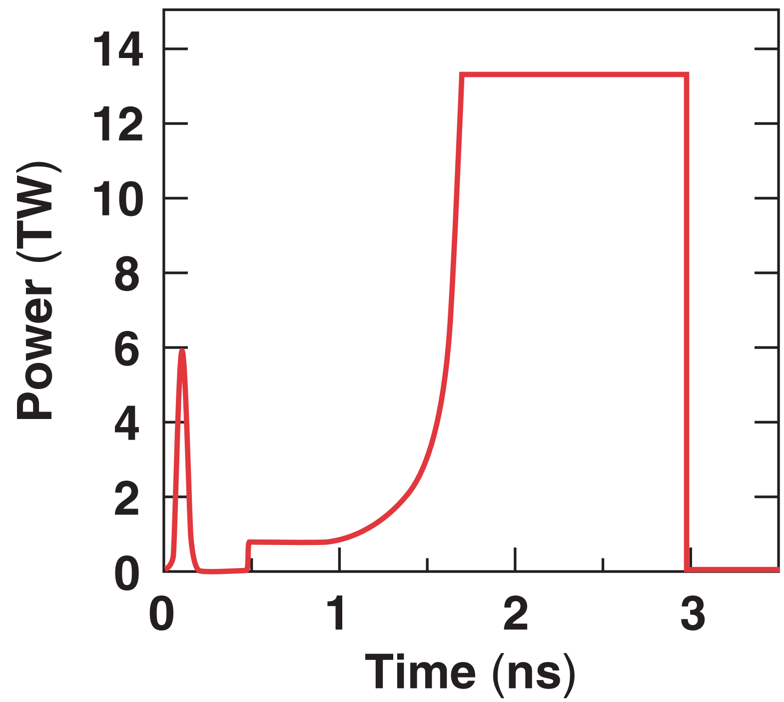
The 130-μm, α = 1, OMEGA-compatible capsule yields a density > 300 g/cc over a ρR > 0.4 g/cm^2 and a hot-spot volume < 20% of the total volume



TC7076

This method for assemblying FI fuel will be first tested on OMEGA with surrogate plastic-shell implosions





Energy	α	Implosion velocity	Maximum ρR (5–15 atm)	Maximum ρ (5–15 atm)	Proton yield (5–15 atm)
20 kJ	1.2	$2.1 \cdot 10^7$ cm/s	0.5–0.36 g/cm^2	276–190 g/cc	$1.2–2.3 \cdot 10^8$

TC7082a

Summary/Conclusions

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UR LLE

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TC7084a