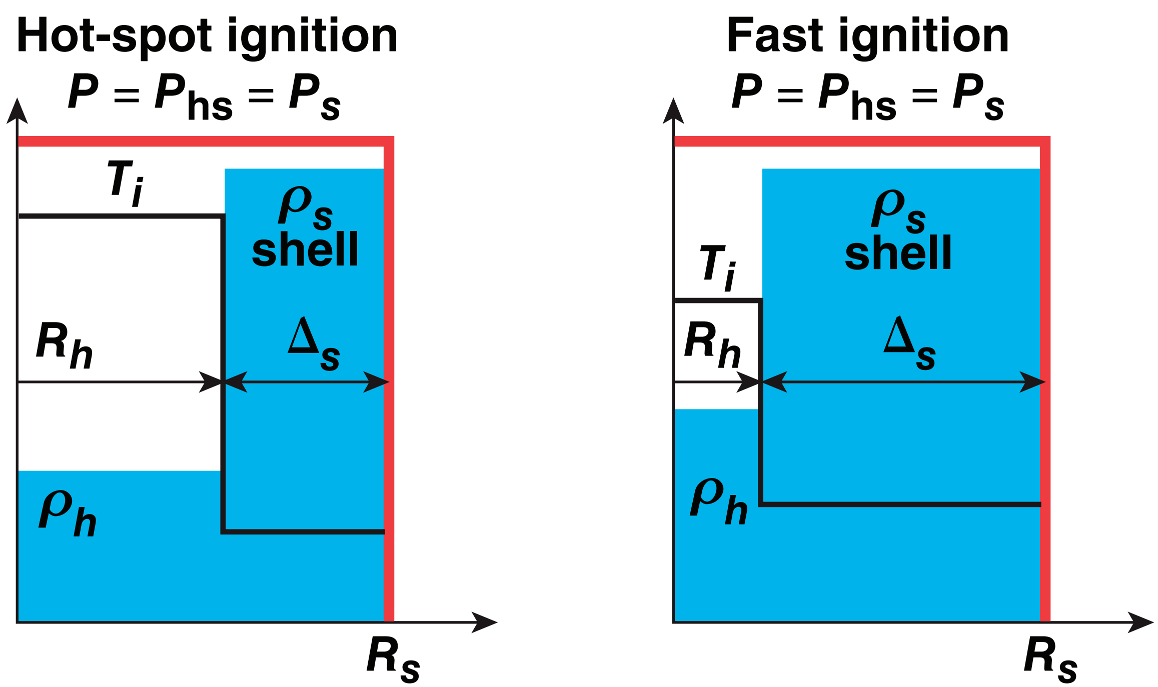
Fast-Ignition Fuel Assembly



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Summary

Scaling laws for fast-ignition fuel assembly are derived and used to design high-density and high-areal-density implosions

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- High-density and high-areal-density capsules are optimized for fast-ignition implosions.
- Density depends on adiabat and implosion velocity. It is independent of driver energy.
- Areal density depends on adiabat and driver energy, and depends weakly on implosion velocity.
- Hot-spot temperature depends only on the implosion velocity.
- Low-adiabat, low-implosion-velocity cryogenic implosions on OMEGA can achieve areal densities up to 0.78 g/cm^2.

TC7576

Energy gain increases for low-implosion velocity and high areal density

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$$G = \frac{\theta E_f / m_{ion}}{V_i^2 / \eta_h} = \frac{\eta_h}{V_i^2} \frac{\theta}{E_f m_{ion}}$$

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

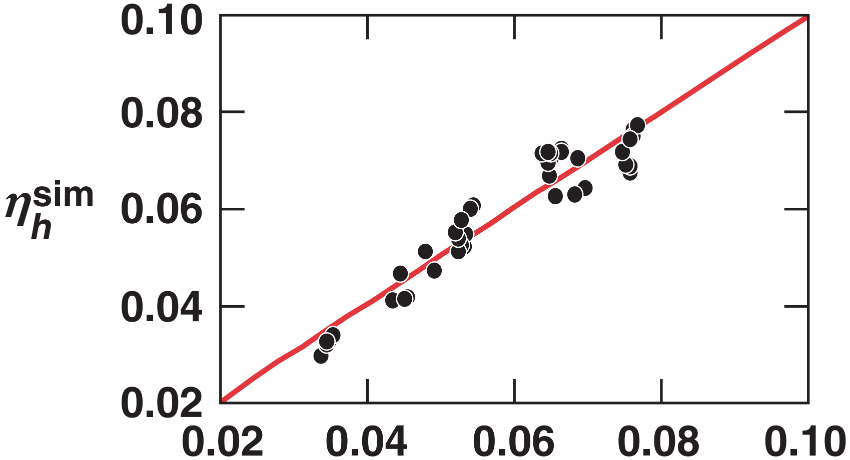
m_i = ion mass

E_f = 17.5 MeV

η_h = hydrodynamic efficiency

Gain formula $\Rightarrow$ $G = \dfrac{73}{I_{15}^{0.25}} \left(\dfrac{3 \times 10^7}{V_i}\right)^{1.25} \left(\dfrac{\theta}{0.2}\right)$

$\eta_h^{theory} \sim V_i^{0.87} \, I_L^{-0.29}$

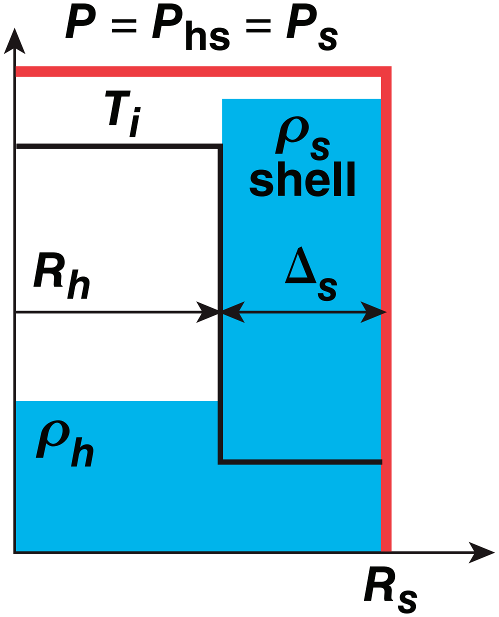


$$\eta_h^{fit} = \frac{0.049}{I_{15}^{0.25}} \left[\frac{V_i \, (cm/s)}{3 \times 10^7}\right]^{0.75}$$

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

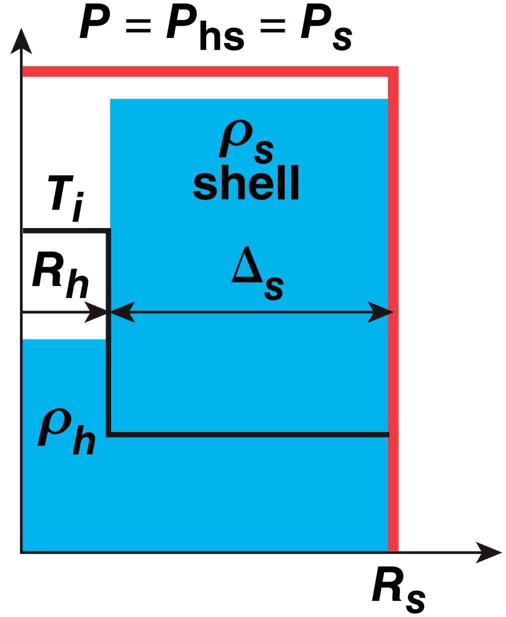
Hot-spot ignition

$P = P_{hs} = P_s$



Fast ignition

$P = P_{hs} = P_s$



Mass: $\rho_s \Delta_s \sim \dfrac{M_{sh}}{R_h^2 \Sigma(A_s)} \sim \dfrac{E_k}{R_h^2 V_i^2 \Sigma(A_s)}$

Energy: $E_k \sim P_s (R_h + \Delta_s)^3$

Entropy:* $\alpha_s \sim \alpha_{if} \, \text{Mach}_{if}^{2/3}$

Aspect ratio: $A_s = \dfrac{R_h}{\Delta_s}$

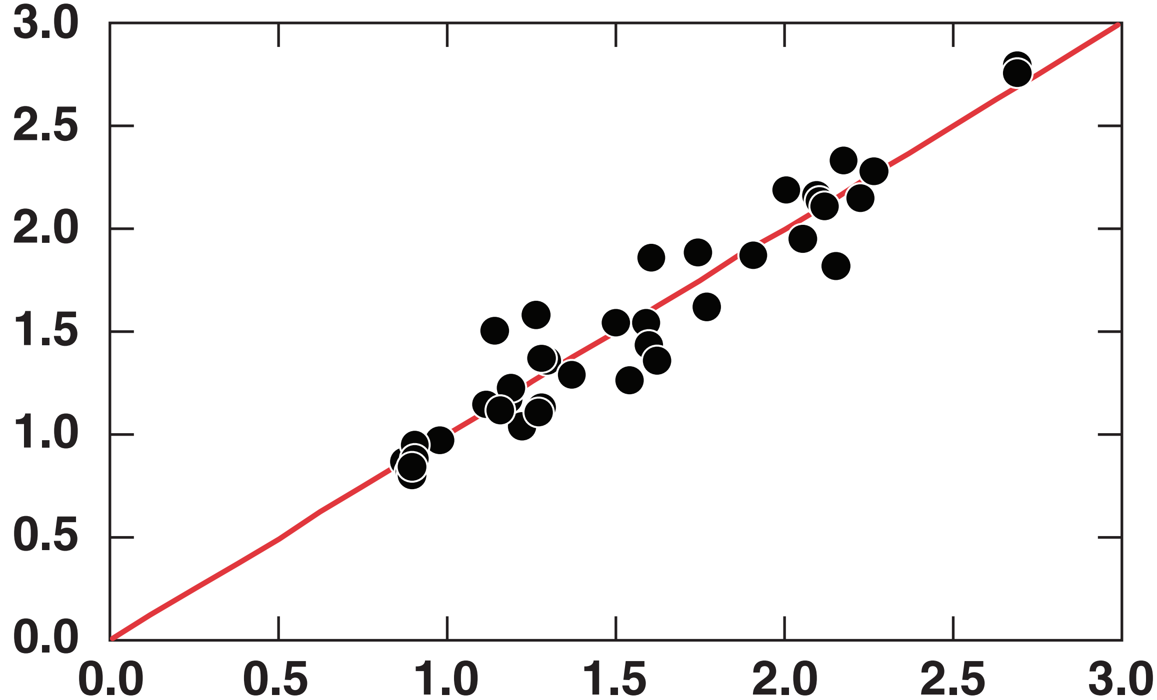
Volume factor: $\Sigma(x) \equiv 1 + \dfrac{1}{x} + \dfrac{1}{3x^2}$

Unknowns: → $P_s, \rho_s, A_s, \Delta_s$

TC7578

*R. Betti *et al*., Phys. Plasmas 9, 2277 (2002).

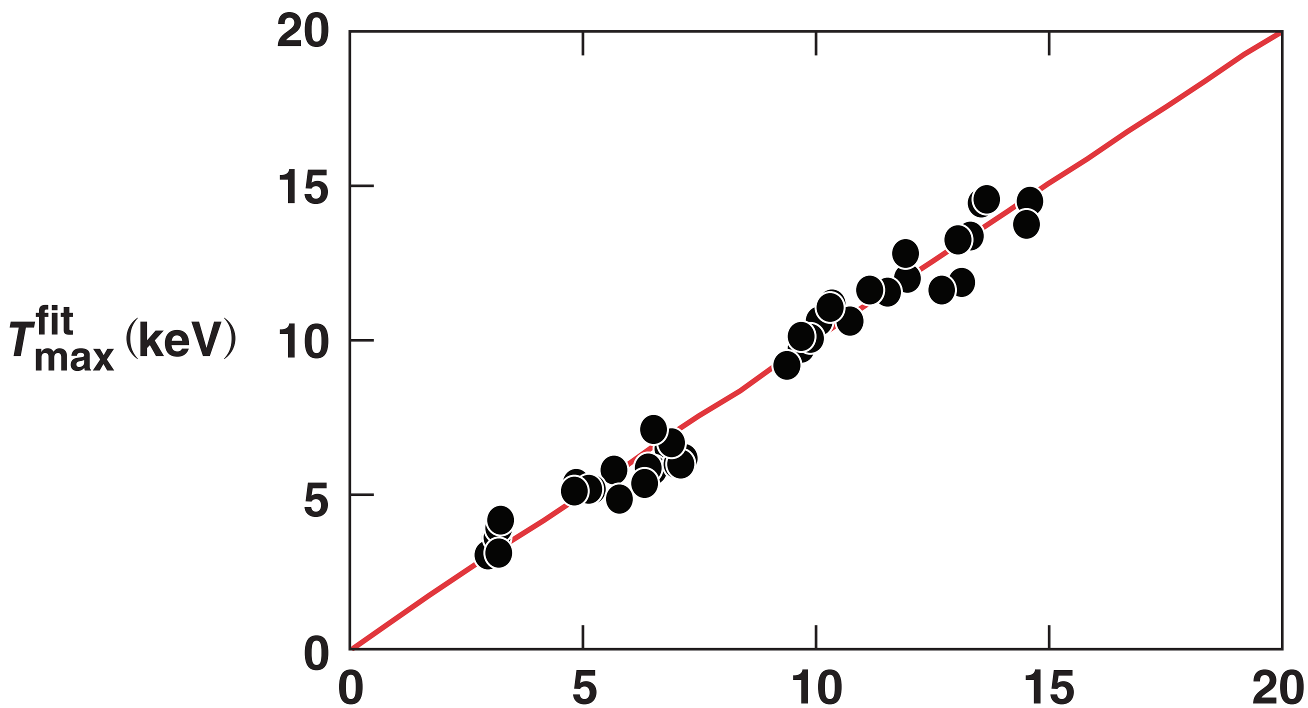
The stagnation aspect ratio decreases with lower implosion velocity



$$A_s^{\mathrm{sim}} = \frac{R_h}{\Delta_s}$$

$$A_s^{\mathrm{fit}} = 2.1\left[\frac{V_i\,(\mathrm{cm/s})}{3\times10^7}\right]^{0.96}$$

The hot-spot temperature decreases with lower velocity



$$T^{max}_{hot\,spot}(\text{keV})^{fit} = 7\left[\frac{V_i\,(\text{cm/s})}{3\times10^7}\right]^{1.4} \alpha^{-0.04}$$

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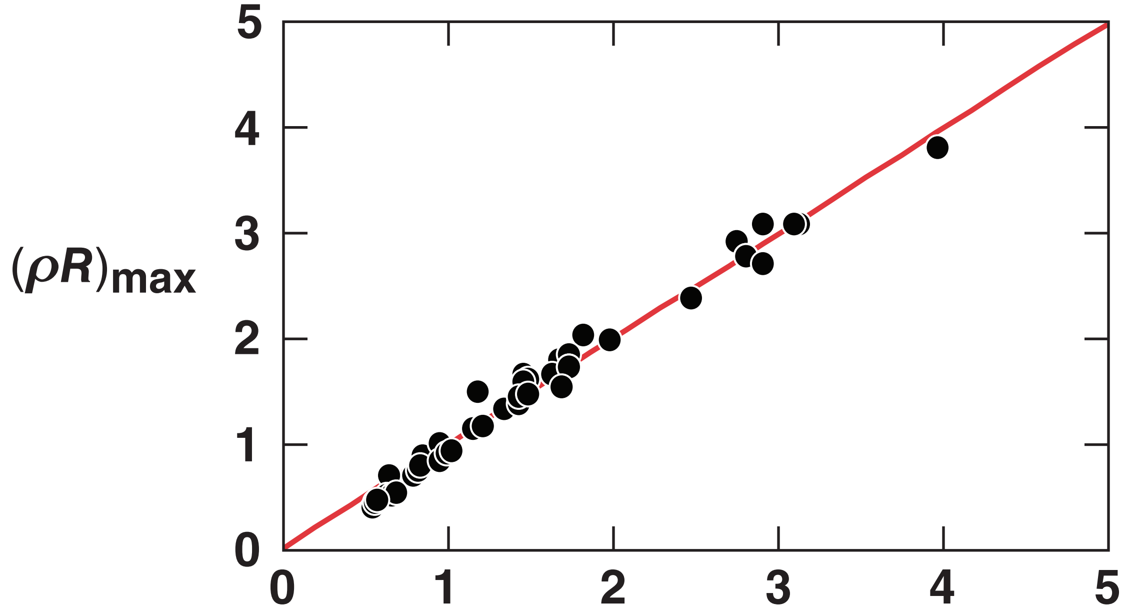
The areal density is dependent on adiabat and driver energy

$$(\rho R)^{\text{theory}} \sim E_L^{0.33}\, \alpha_{\text{if}}^{-0.8}\, V_I^{0.03}$$



$$(\rho R)_{\text{max}}^{\text{fit}} = \frac{1.2}{\alpha^{0.57}}\left[\frac{E_L\,(\text{kJ})}{100}\right]^{0.33}\left[\frac{V_i\,(\text{cm/s})}{3\times10^7}\right]^{0.1}$$

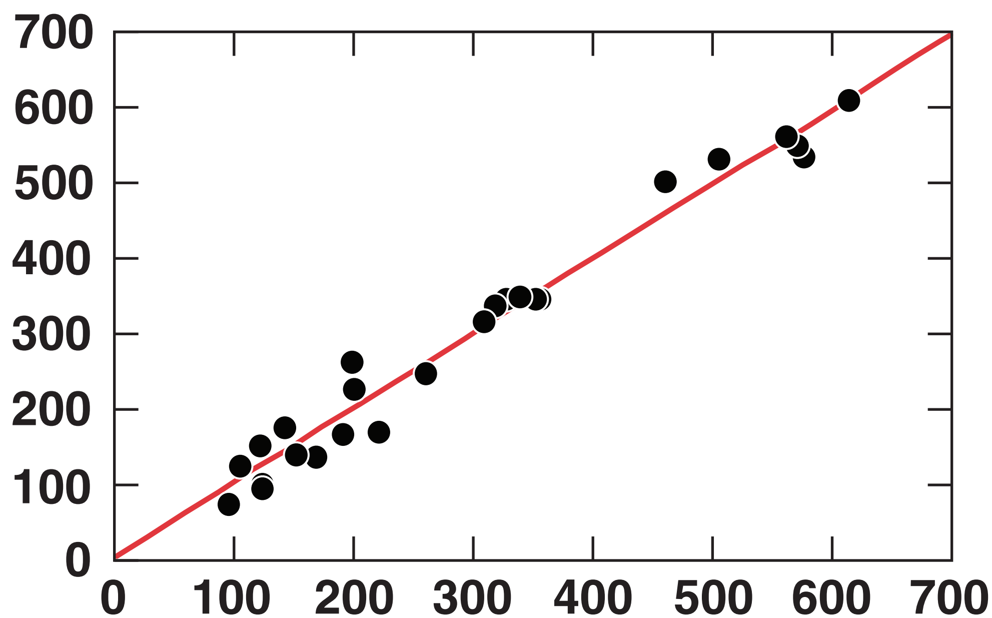
TC7581

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

Fast ignition requires large enough densities; the density depends on velocity and adiabat

$$\rho_s^{\text{theory}} \sim V_I^{1.4}\,\alpha_{\text{if}}^{-1.2}$$

$\langle \rho \rangle_{\rho R}$



$$\langle \rho R \rangle_{\rho R}^{\text{fit}} = \frac{440}{\alpha^{1.03}}\left[\frac{V_i\,(\text{cm/s})}{3\times 10^{7}}\right]^{0.93}$$

TC7582

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

The hydrodynamics of fast ignition depend on three parameters: gain, density, and areal density

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$$\text{Gain} \sim V_i^{-1.25}\left(1 + 7/\rho R\right)^{-1} \Longrightarrow \frac{743}{1 + 30\Big/ E_L^{1/3}(\text{kJ})}$$

$$\rho R \sim E_L^{0.33}\Big/\alpha^{0.57}$$

$$\rho \sim V_i/\alpha$$

$$E_{ig}^{*}(kJ) \approx 11\left[\frac{400}{\rho(\text{g/cc})}\right]^{1.95}$$

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

- Fast-ignition implosion
  - low-velocity V_i
  - low-adiabat α
  - large mass

High ρ is required for fast ignition

Upper bound of the density

*S. Atzeni, Phys. Plasmas 6, 3316 (1999).

TC7583

Low-adiabat implosions lead to high ρ and ρR with low velocities, large masses, and high gains

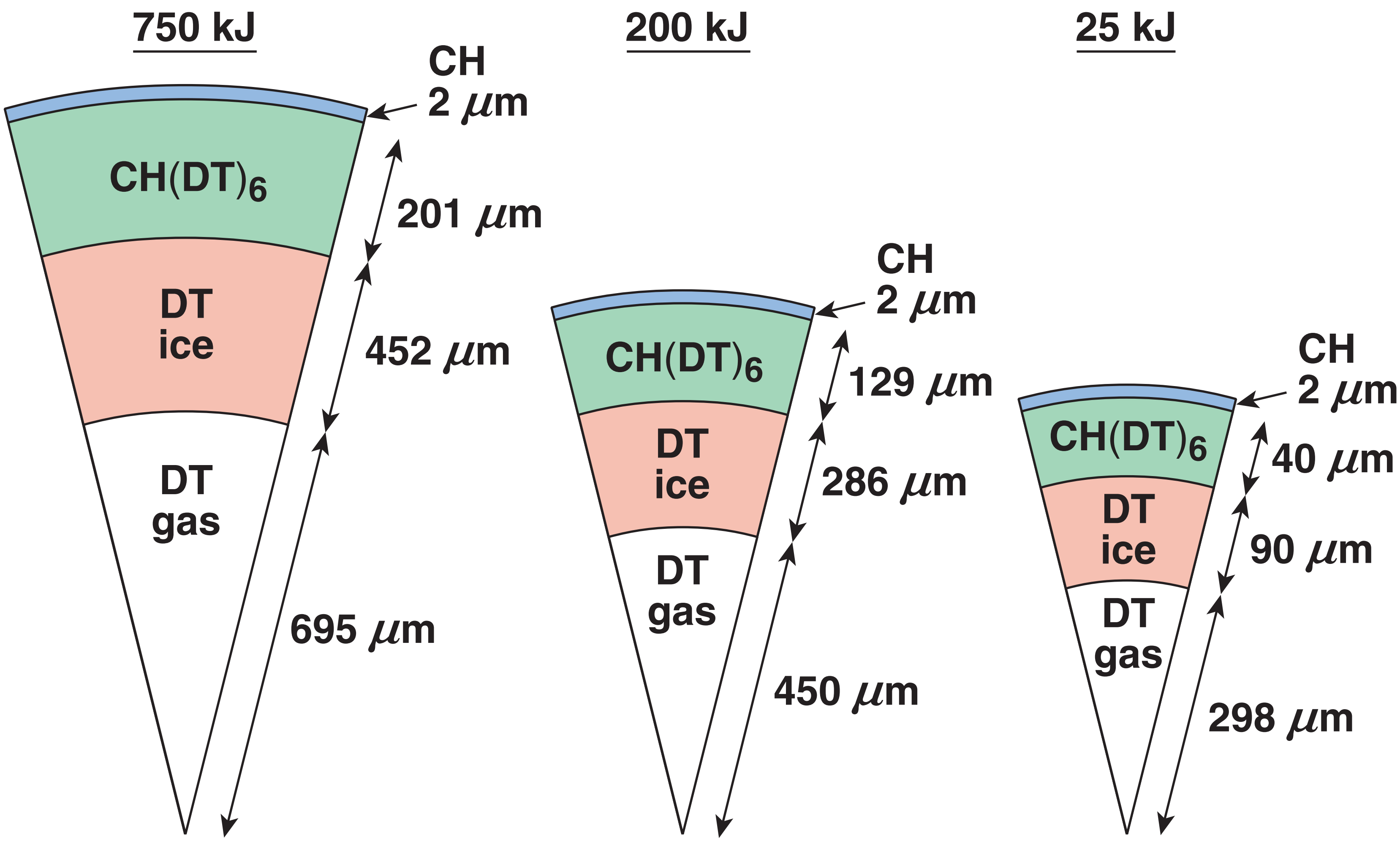
Implosion Characteristics

- Choose the lowest possible adiabat. Limitation to the minimum adiabat comes from the laser pulse length and the pulse contrast ratio; $\alpha = 0.7$ seems a reasonable value
- Choose stagnation density
- Find the implosion velocity from the density equation

Target Design

- Set $I \approx 10^{15}$ W/cm^2
- Choose driver energy and corresponding laser power
- Find capsule outer radius from power and intensity
- Find final mass from kinetic energy
- Assuming a 20% ablated mass leads to an initial mass
- Initial mass and outer radius yield the inner radius

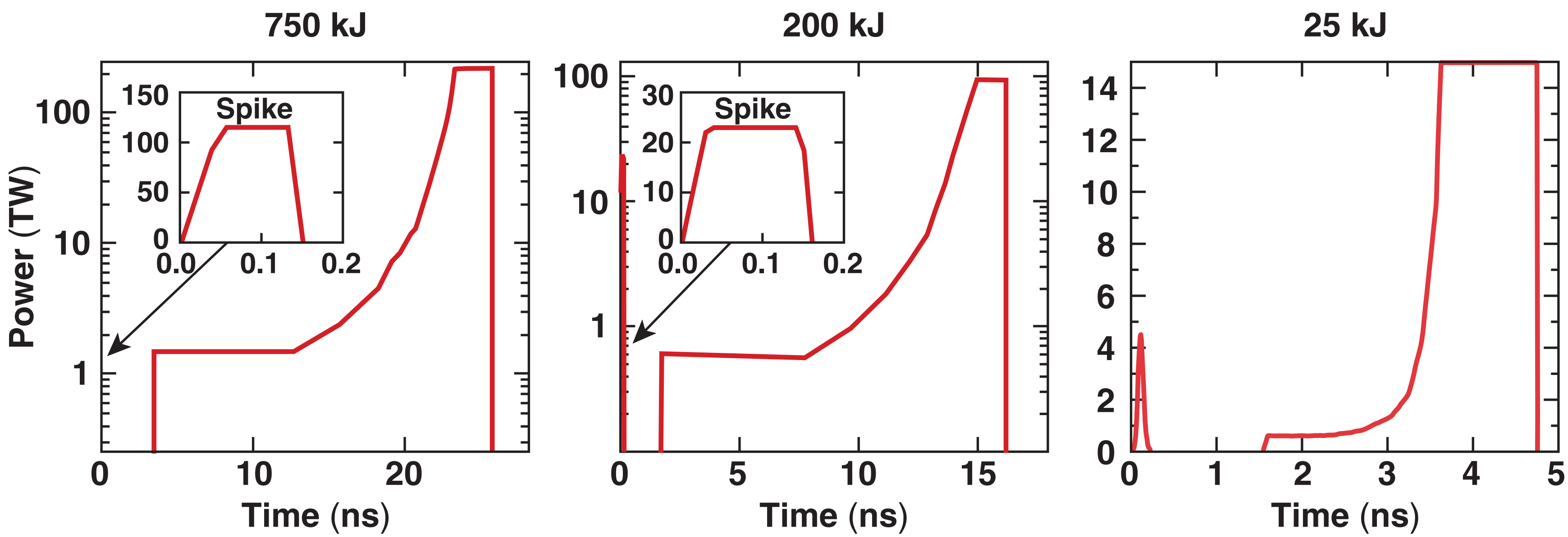
Optimized fast-ignition cryo targets are thick shells of wetted foam with an initial aspect ratio of ~2



TC7585

R. Betti *et al.*, Physics of Plasmas (in press).

These targets have high areal densities and low IFAR



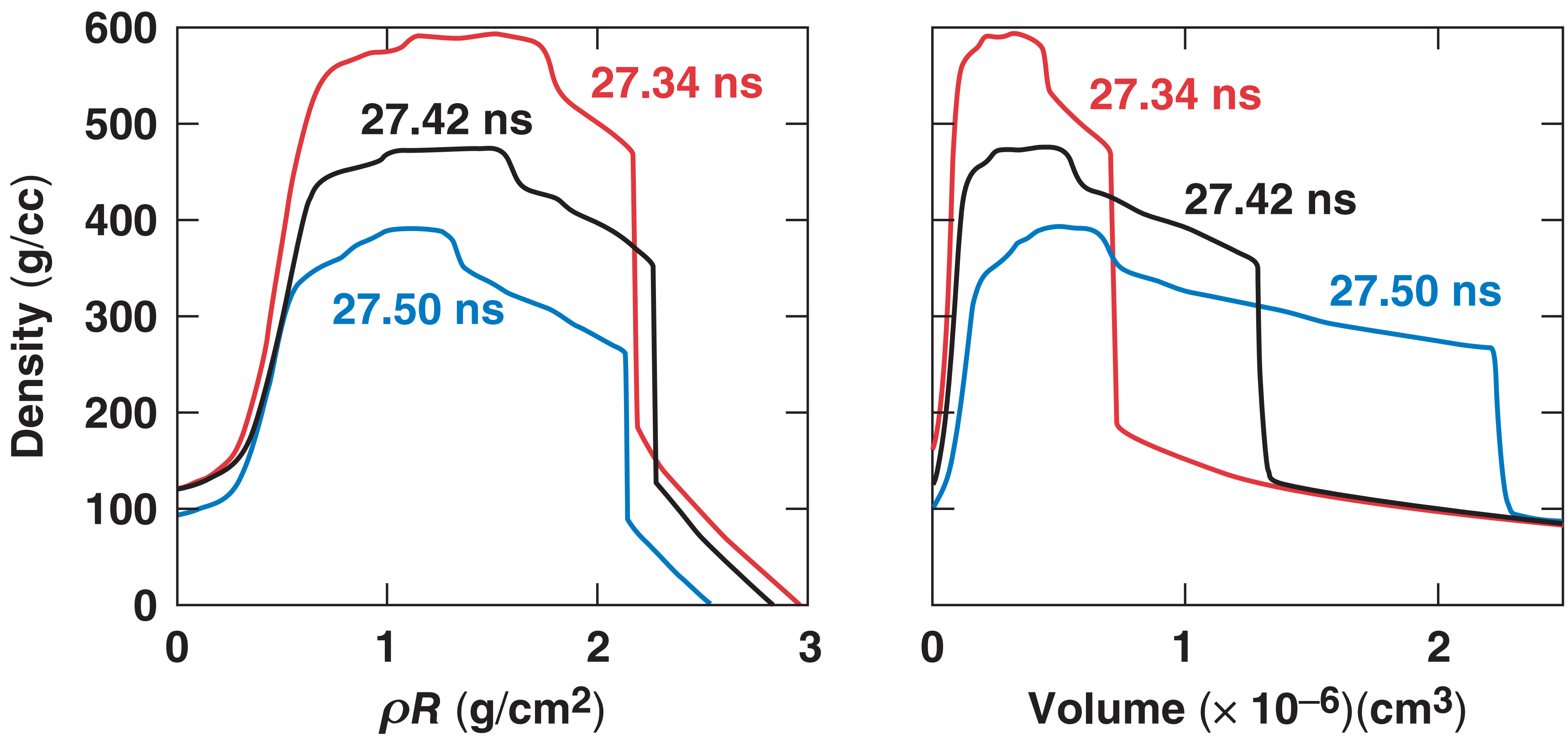
Maximum ρR	3 g/cm^2
α	0.7
V_i	1.7×10^7 cm/s
IFAR	18

Maximum ρR	1.9 g/cm^2
α	0.7
V_i	1.7×10^7 cm/s
IFAR	18

Maximum ρR	0.78 g/cm^2
α	1.0
V_i	2.6×10^7 cm/s
IFAR	30

Low-adiabat implosions are driven by RX laser pulses.

The 750-kJ capsule yields a density >300 g/cc over a $\rho R > 2$ g/cm^2



The hot-spot volume is <8% of the compressed volume.

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Summary/Conclusions

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