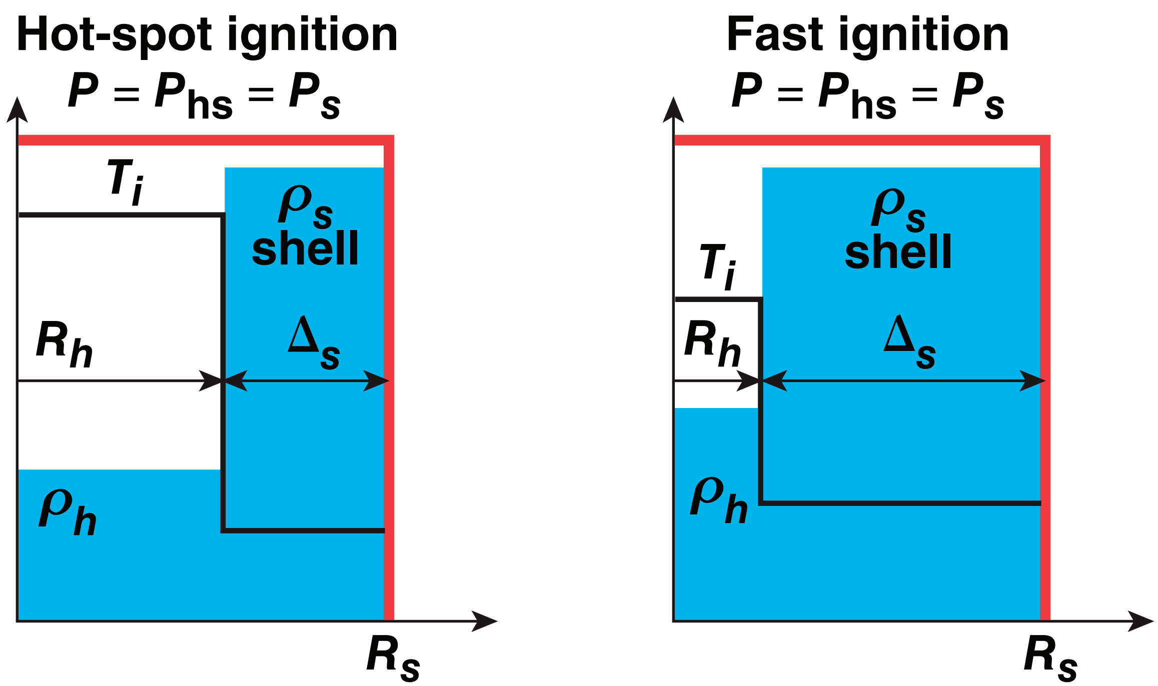
Fast-Ignition Fuel Assembly: Theory and Experiments



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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.

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

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

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

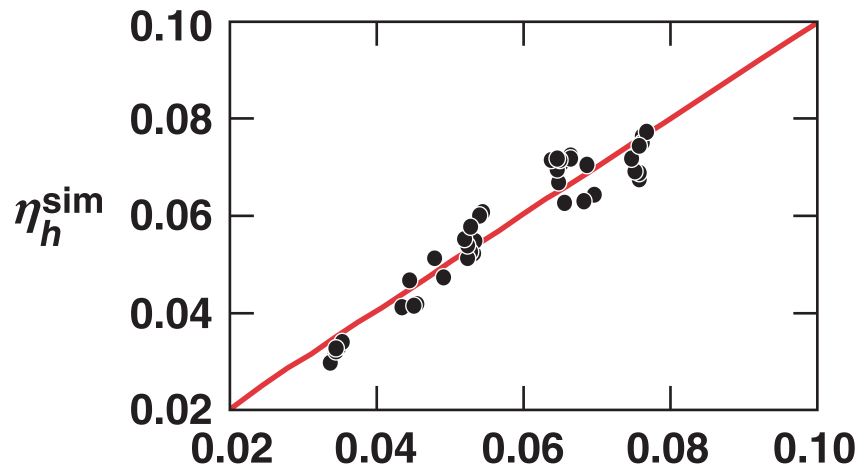
m_i = ion mass

E_f = 17.5 MeV

η_h = hydrodynamic efficiency

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

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



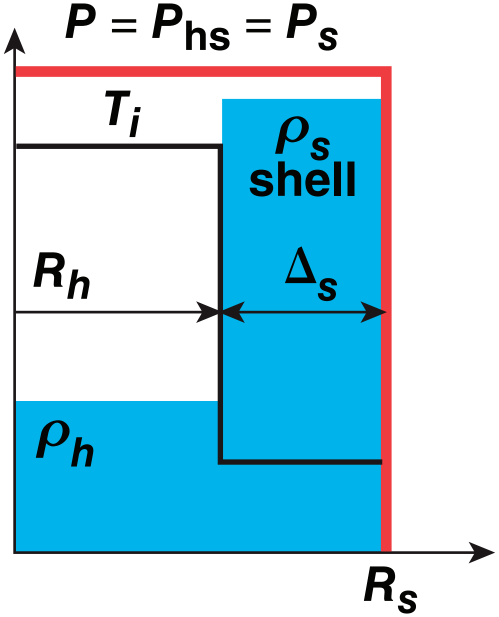
$$\eta_h^{fit} = \frac{0.049}{I_{15}^{0.25}} \left[\frac{V_i\,(\text{cm/s})}{3 \times 10^7} \right]^{0.75}$$

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

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

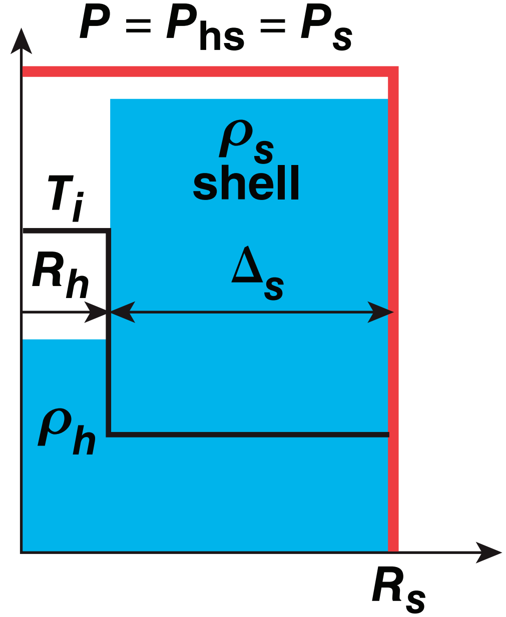
Hot-spot ignition

$P = P_{hs} = P_s$



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

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

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

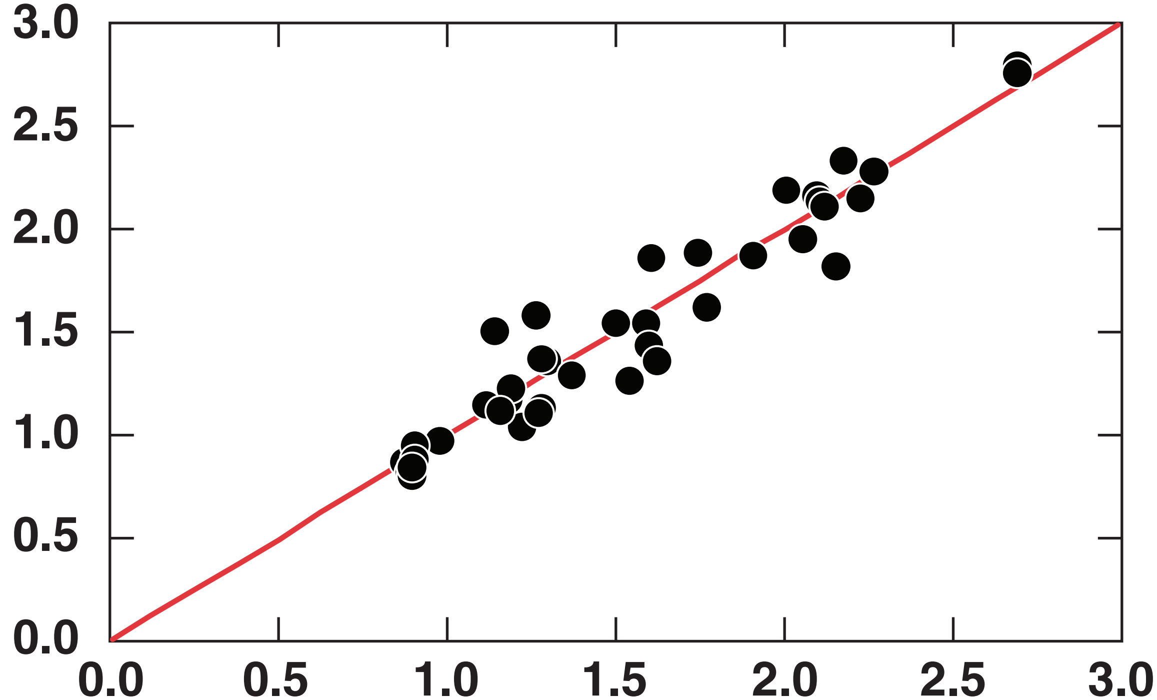
Unknowns: → $P_s, \rho_s, A_s, \Delta_s$

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

TC7578

The stagnation aspect ratio decreases with lower implosion velocity

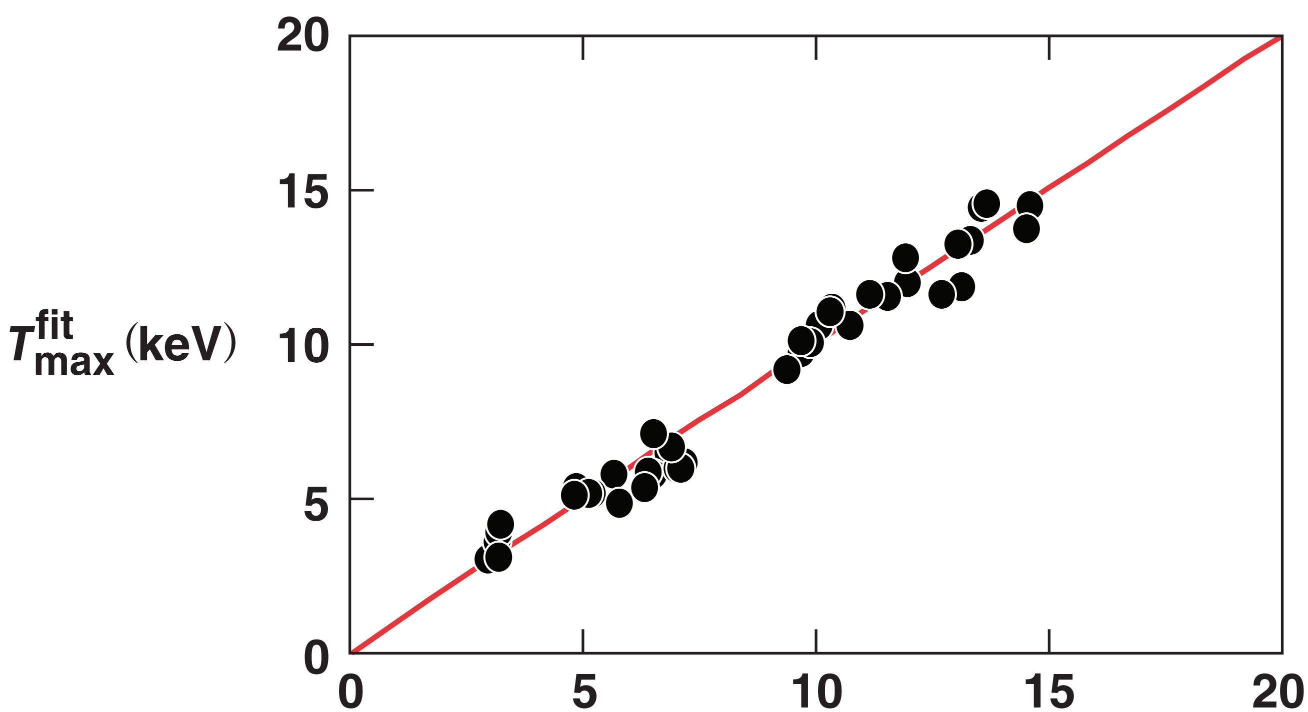
$$A_s^{sim} = \frac{R_h}{\Delta_s}$$



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

TC7579

The hot-spot temperature decreases with lower velocity

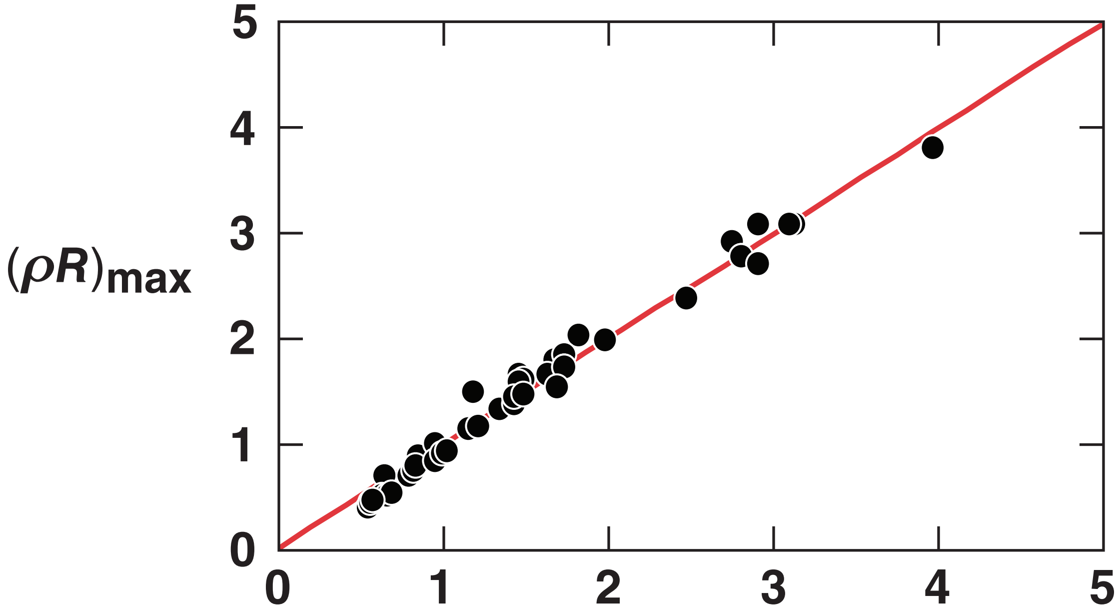


$$T_{hot\,spot}^{max}(\text{keV})^{fit} = 7\left[\frac{V_i\,(\text{cm/s})}{3\times10^7}\right]^{1.4}\alpha^{-0.04}$$

TC7580

The areal density is dependent on adiabat and driver energy

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



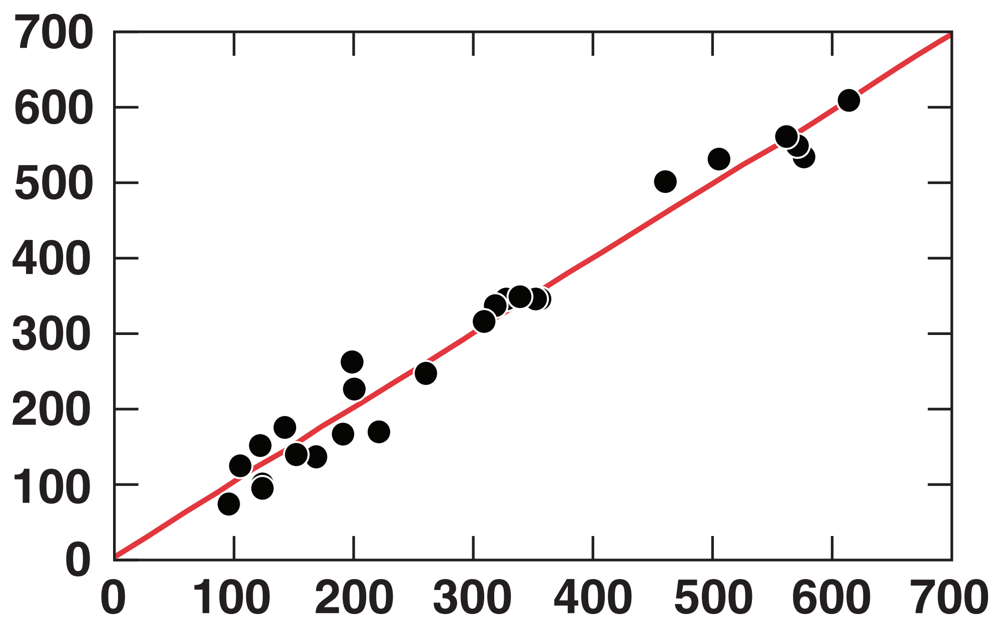
$$(\rho R)_{max}^{fit} = \frac{1.2}{\alpha^{0.57}}\left[\frac{E_L\,(\text{kJ})}{100}\right]^{0.33}\left[\frac{V_i\,(\text{cm/s})}{3\times10^7}\right]^{0.1}$$

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

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

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

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

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

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

High ρ is required for fast ignition

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

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

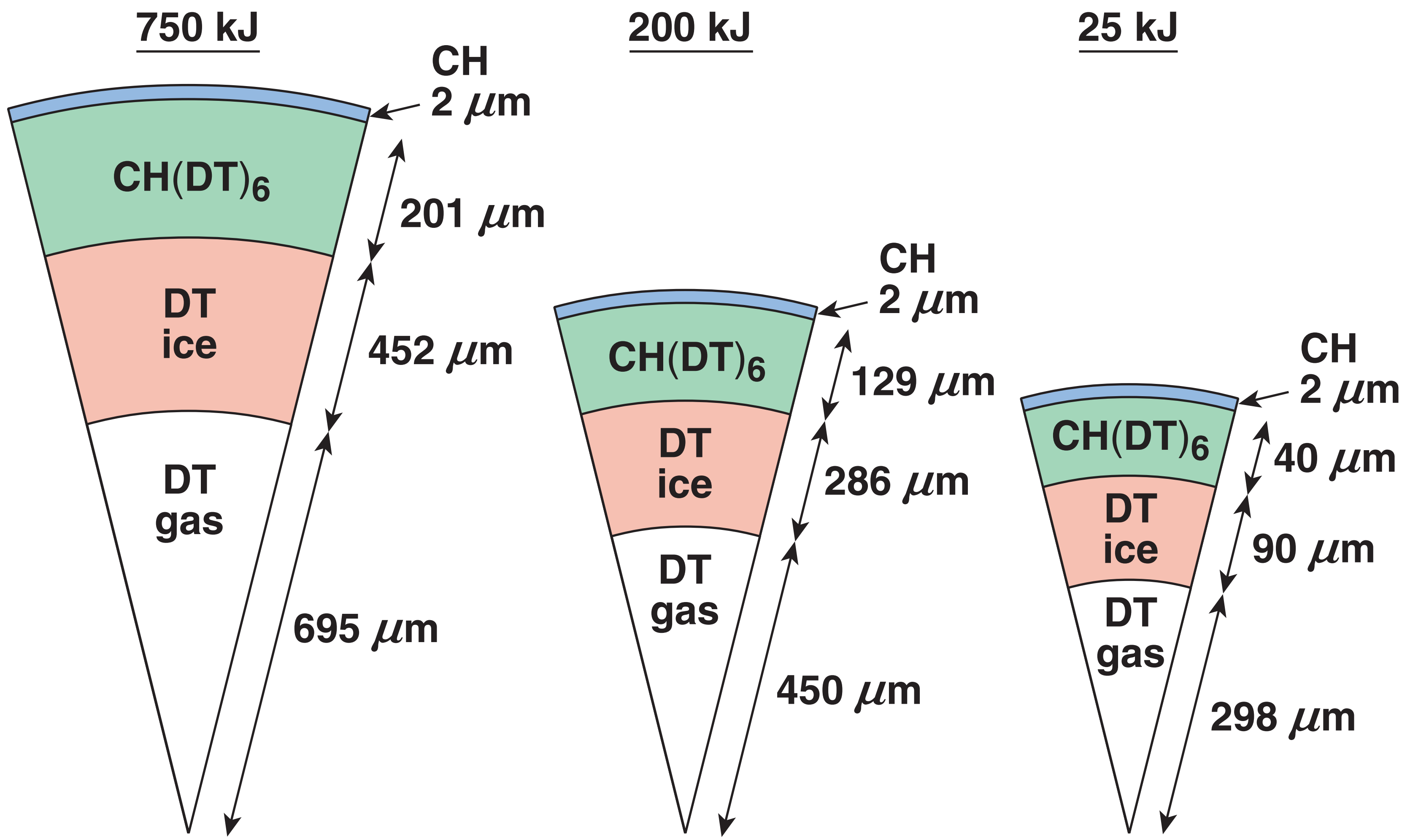
Implosion Characteristics

- 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

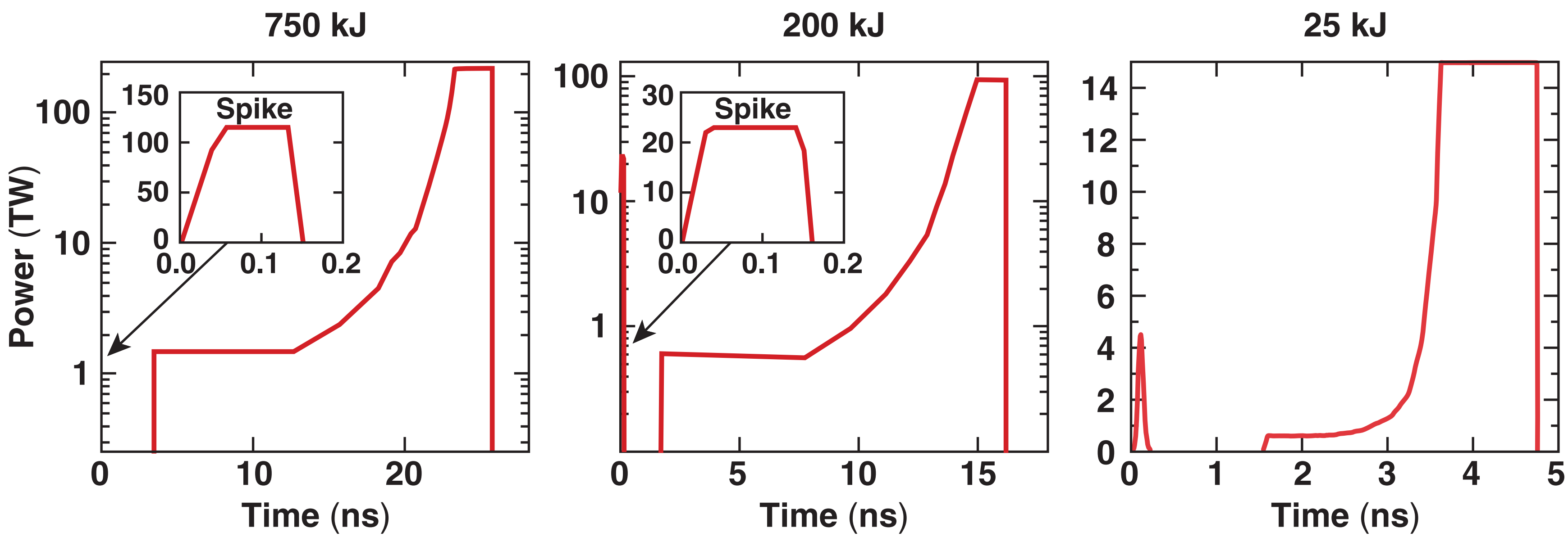
Optimized fast-ignition cryo targets are thick shells of wetted foam with an initial aspect ratio of ~2



TC7585

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

These targets have high areal densities and low IFAR



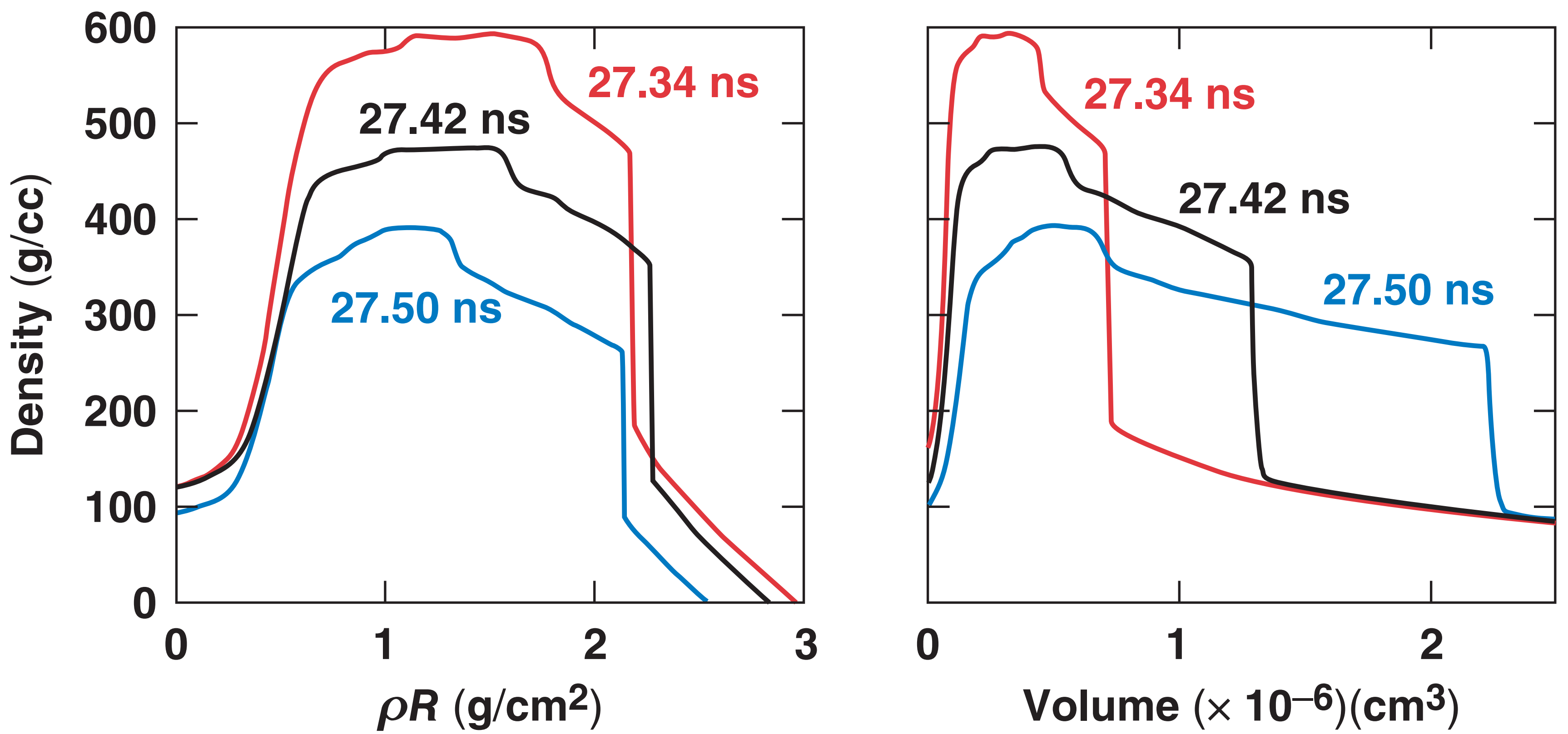
Maximum ρR	3 g/cm^2
α	0.7
V_i	1.7×10^7 cm/s
IFAR	18

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 ρR > 2 g/cm^2

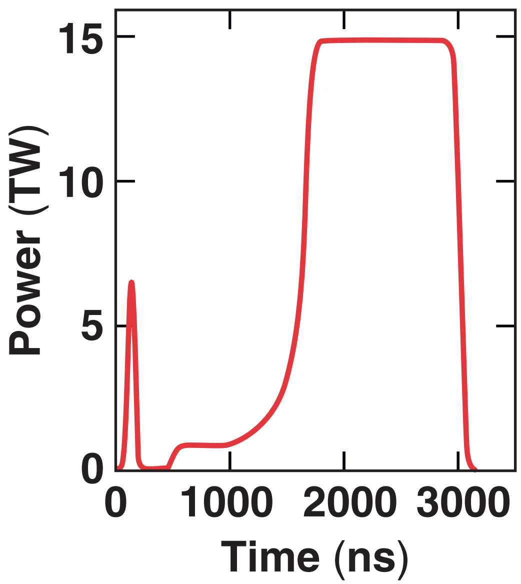


The hot-spot volume is <8% of the compressed volume.

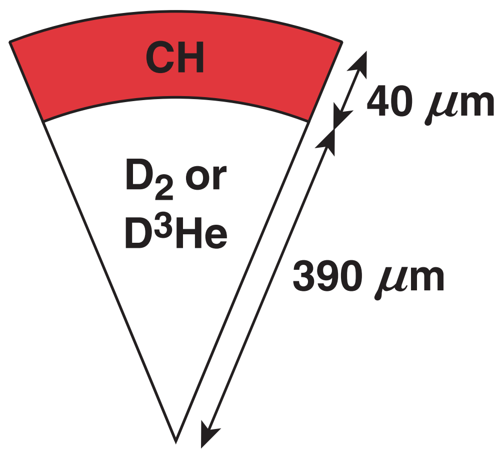
TC7587

Low-adiabat, low-V_i implosions of surrogate CH targets are used to study fast-ignition fuel assemblies on OMEGA

RX laser pulse



Target



Simulated values

Pressure (atm)	ρ (g/cc)	$2\rho R$ (g/cm^2)	E_{stop} (MeV)*
35	89.3	0.52	2.10
25	101	0.62	2.35
15	120	0.74	2.76
5	185	1.02	3.53
1	222	1.32	4.45

$E_L \approx 20$ kJ, $\alpha \approx 1.3$,

$V_i \approx 2 \cdot 10^7$ cm/s

TC7640

*C. K. Li and R. D. Petrasso, Phys. Rev. E 70, 067401 (2004).

The DD neutron production begins as predicted and shows a 200-ps truncation, probably due to hot-spot CH–DD mixing

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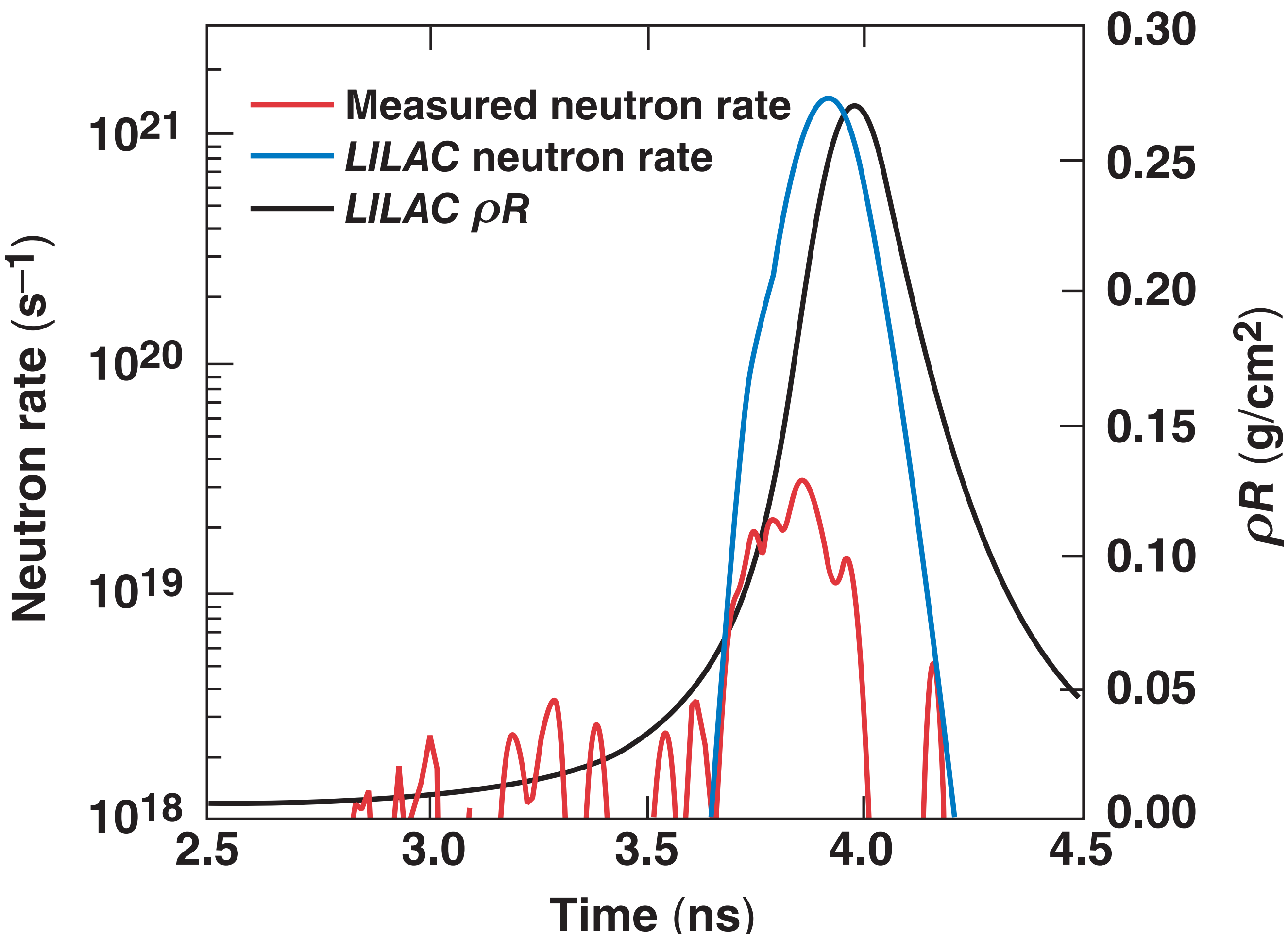
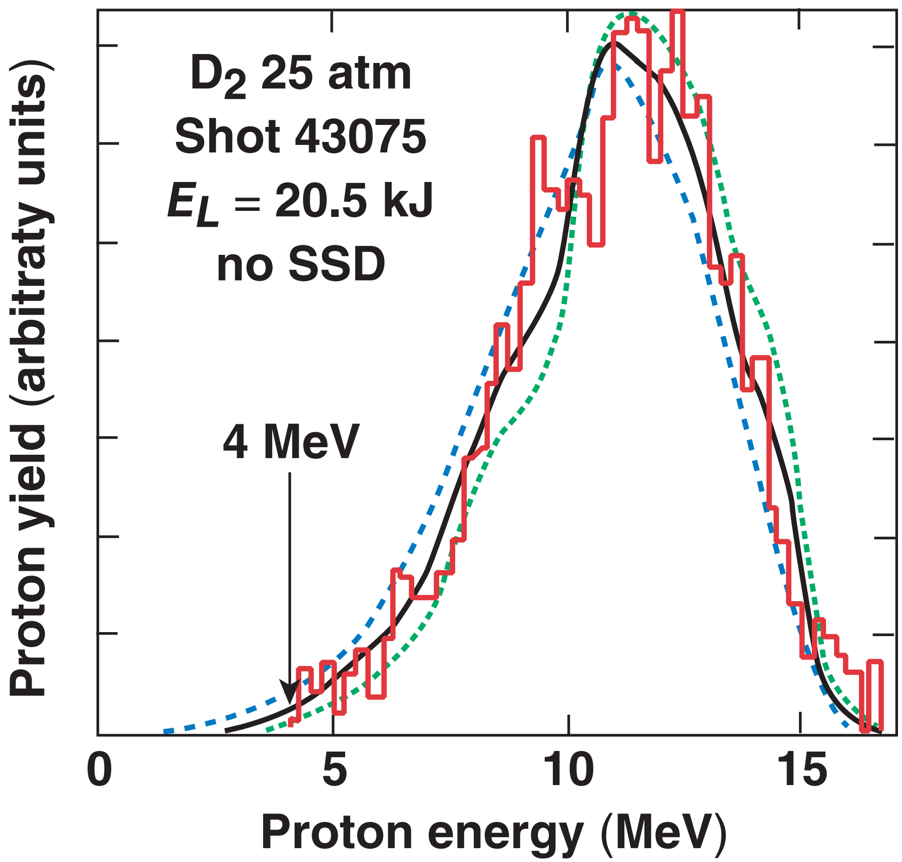


D_2 25 atm
Shot # 43075
E_L = 20.5 kJ
No SSD

YOC = 3%

E15249a

The measured[1] and reconstructed[2] downshifted secondary proton spectra are in good agreement



The reconstruction used the measured neutron rate and the simulated $\rho R(t)$.

- Measured spectrum
- *LILAC* with 1-D source size
- *LILAC* with point source
- *LILAC* averaged

8.7-MeV downshift

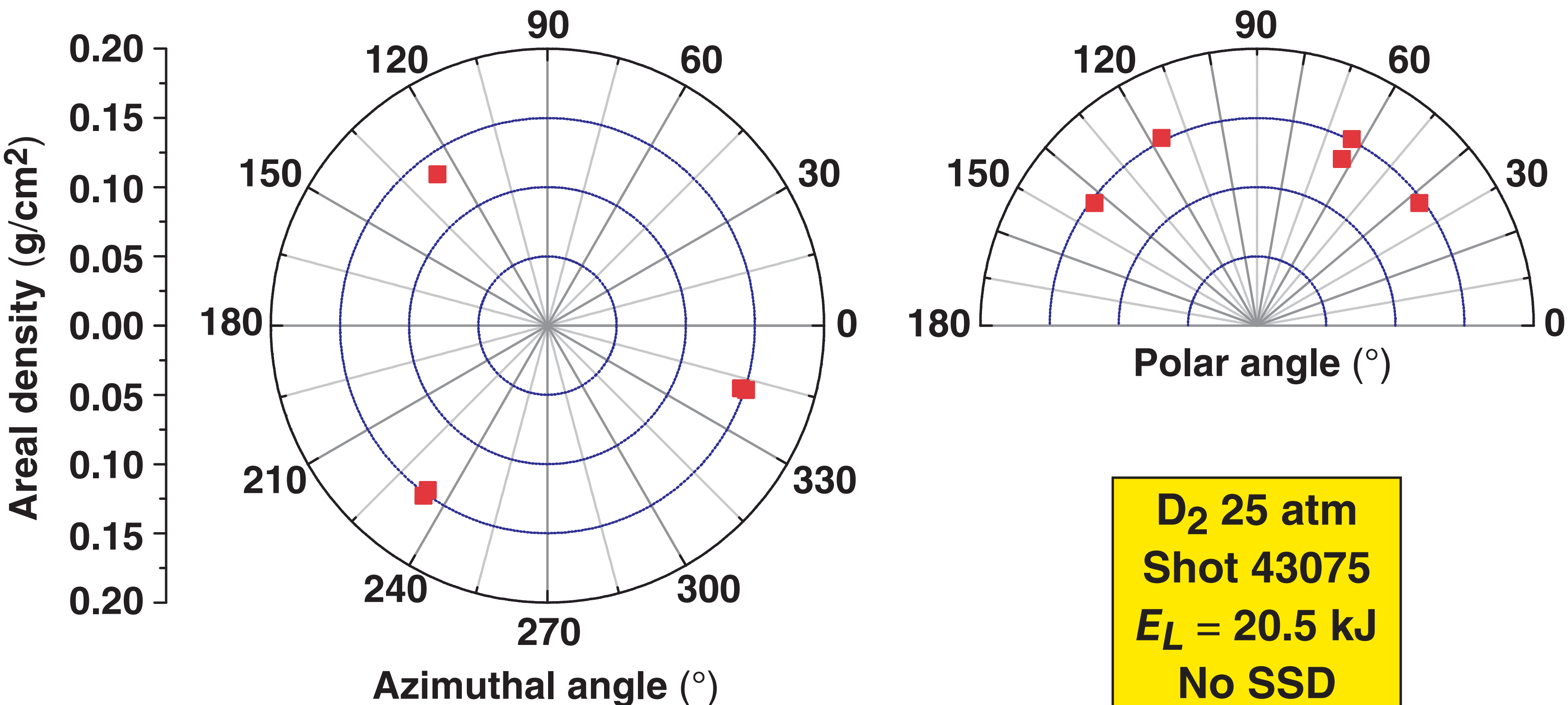
$(\rho R)_{max} = 0.26\ g/cm^2$

$\langle \rho R \rangle_n = 0.15\ g/cm^2$

[1]F. H. Séguin *et al*., Rev. Sci. Instrum. 74, 975 (2003).
[2]P. B. Radha *et al*., APS/DPP 2006 (GO2.00008).

E15250

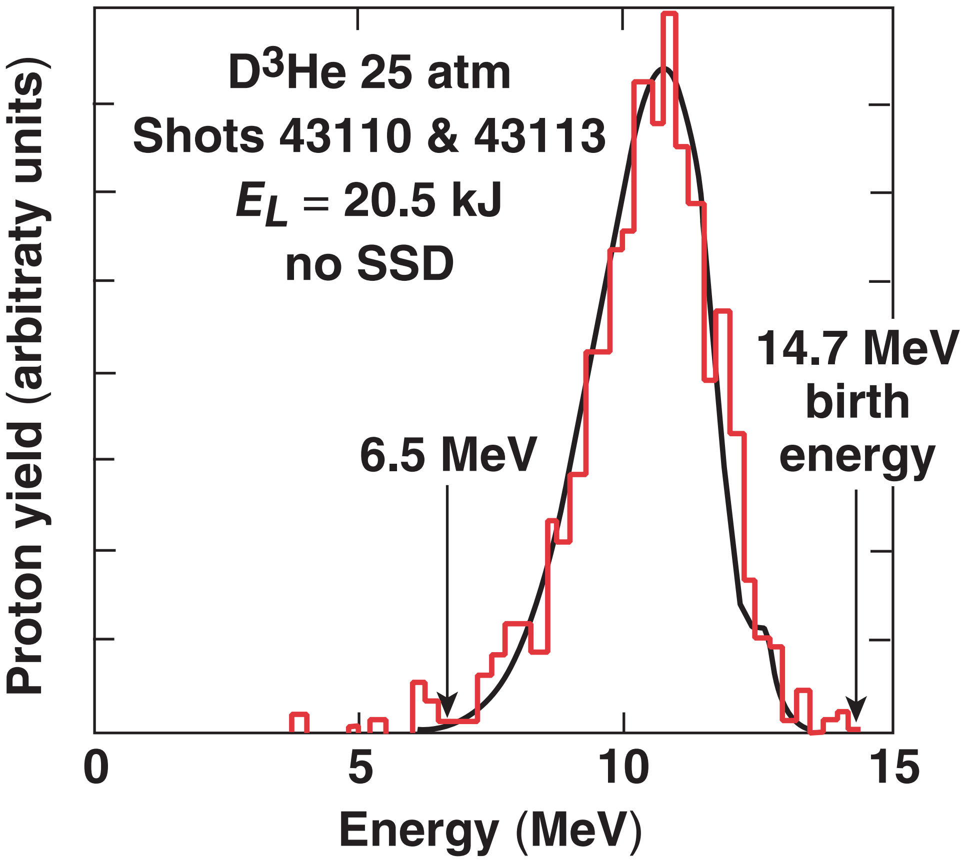
The ⟨ρR⟩ modulations are <10%, indicating that the compressed core is not significantly affected by low-mode ($\ell \leq 5$) nonuniformities



D_2 25 atm
Shot 43075
E_L = 20.5 kJ
No SSD

E15252

The measured[1] and reconstructed[2] downshifted primary proton spectra are in good agreement for D^3He implosions



The calculation used an estimated proton rate and the simulated ρR evolution

- Measured spectrum
- Calculated spectrum

8.2-MeV downshift

$(\rho R)_{max}$ = 0.24 g/cm^2

$\langle \rho R \rangle_n$ = 0.13 g/cm^2

[1] F. H. Séguin *et al.*, Rev. Sci. Instrum. 74, 975 (2003).
[2] P. B. Radha *et al.*, APS/DPP 2006 (GO2.00008).

E15251

Very good agreement between measured and predicted areal densities is obtained

Shot number	Gas fill	Pressure (atm)	Measured $\langle \rho R \rangle_p$	Sim. shell $\langle \rho R \rangle_n$	Measured ρR_n^{max}	Sim. ρR^{max}
43074	D_2	34	0.133	0.138	0.25	0.24
43075	D_2	25	0.146	0.144	0.26	0.26
43107	D_2	25	0.122	0.132	0.24	0.27
43114	D_2	25	0.128	0.112	0.23	0.23
43106	D_2	13	0.128	—	—	—
43108	D_2	13	0.129	—	—	—
43109 + 43112	D^3He	33	0.128	—	0.24	0.25
43110 + 43113	D^3He	25	0.130	—	0.24	0.28
Average			0.131	0.132	0.24	0.25

E15253a