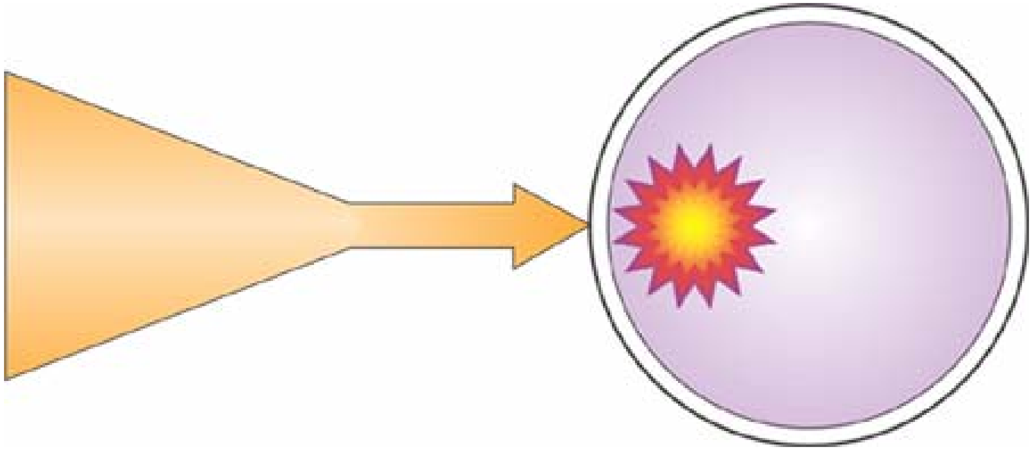
# FUEL ASSEMBLY: THEORY AND EXPERIMENTS



R. Betti, C. Zhou, A. Solodov, W. Theobald,
K. Anderson, C. Stoeckl, D. Meyerhofer
*Fusion Science Center,* LLE
C. Li and R. Petrasso
*Fusion Science Center,* MIT

4th Fusion Science Center Meeting
Livermore, CA
28-29 August 2006

# Outline

- Review of the hydrodynamic theory for fast ignition
- Two dimensional simulations of FI fuel assembly
- Gain curves for fast ignition
- OMEGA experiments for FI fuel assembly on CH targets
- Cryogenic target design for fuel assembly on OMEGA

# High areal densities ($\rho R$) and low-implosion velocities ($V_i$) lead to high energy gains (assuming that ignition occurs)

$$\boxed{G = \frac{E_{Fusion}}{E_{Laser}} \sim \frac{\theta}{V_i^{1.25}}}$$

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

- Higher $\rho R$ → faster burn and longer burn time
- Lower $V_i$ → more fuel mass for the same kinetic/laser energy

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

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

$$\rho R^{a} \sim E_L^{0.33}/\alpha^{0.55}$$

$$\rho^{a} \sim V_i/\alpha$$

$$E_{ig}^{b}(kJ) \approx 11\left(\frac{400}{\rho_{g/cc}}\right)^{1.85}$$

High ρ is required for fast ignition

**Fast ignition implosion:**

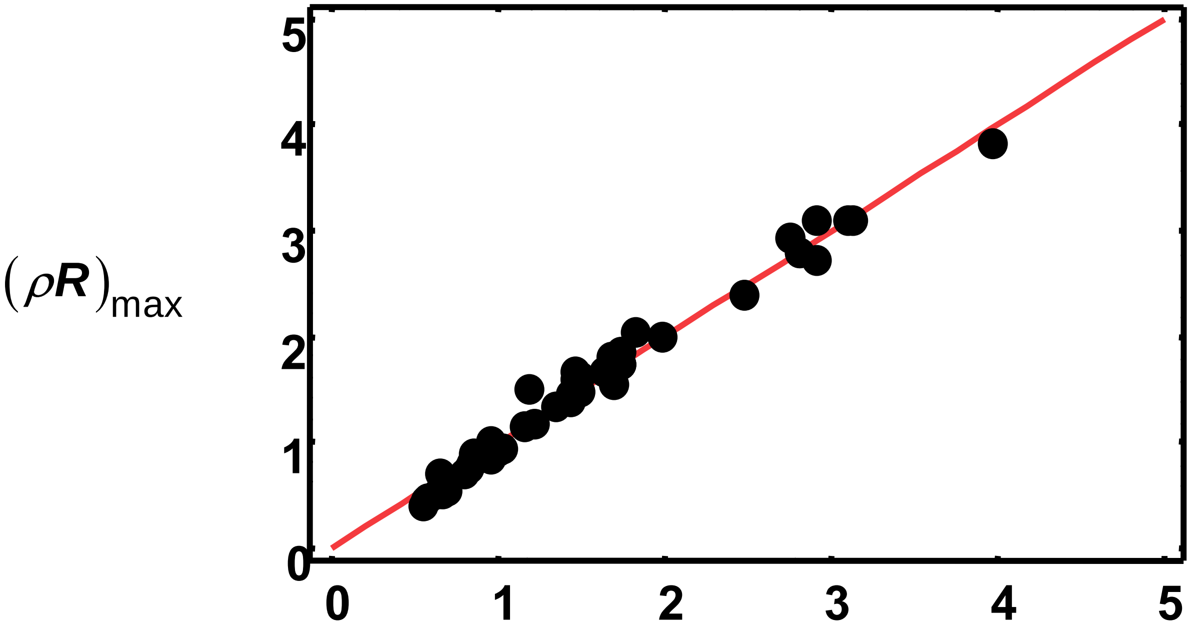
- Low velocity $V_i$
- Low adiabat $\alpha$
- Large mass

---

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

[b] S. Atzeni, Phys. Plasmas 6, 3316 (1999)

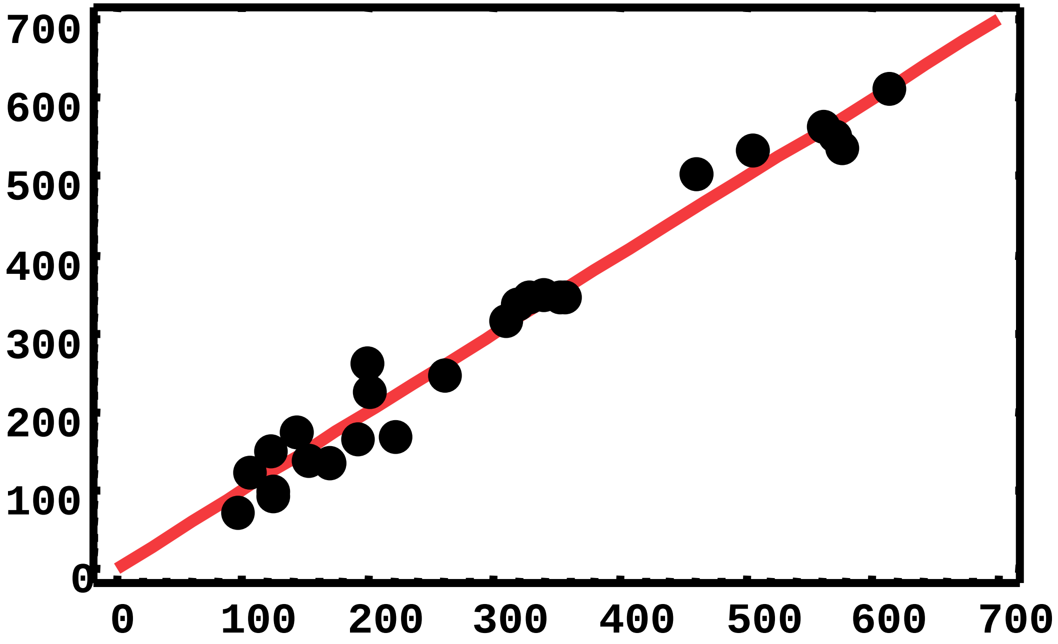
# We have increased the implosion simulation database. The areal density increases for lower adiabats and greater energies. It is independent of velocity.



$$(\rho R)^{fit}_{max} = \frac{1.2}{\alpha^{0.57}}\left(\frac{E_L(kJ)}{100}\right)^{0.35}\left(\frac{V_i(cm/s)}{3\bullet10^{7}}\right)^{0.1}$$

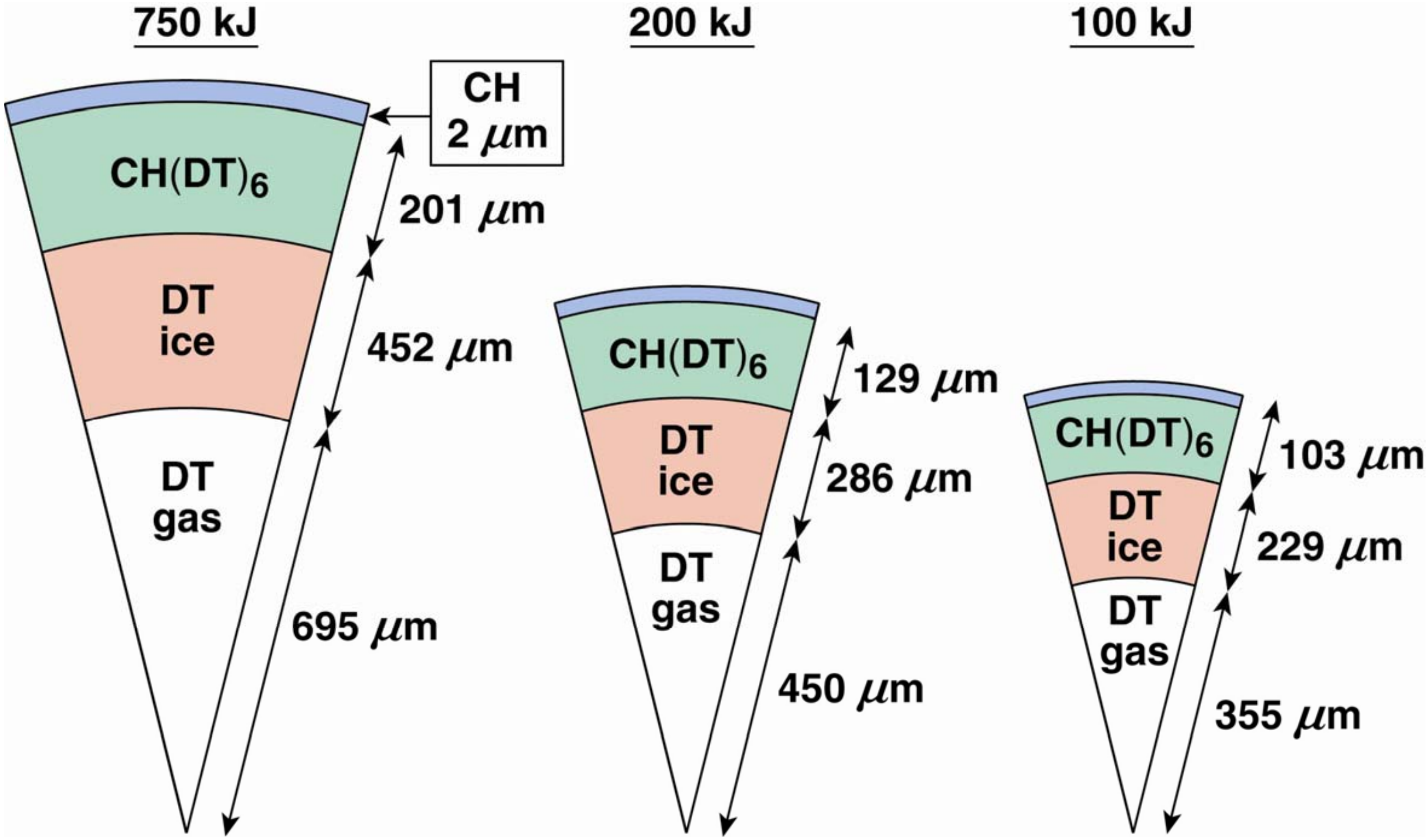
# The density increases with high velocities and lower adiabats

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



$$\langle\rho\rangle^{fit}_{\rho R} = \frac{440}{\alpha}\left(\frac{V_i(cm/s)}{3\bullet 10^7}\right)^{0.93}$$

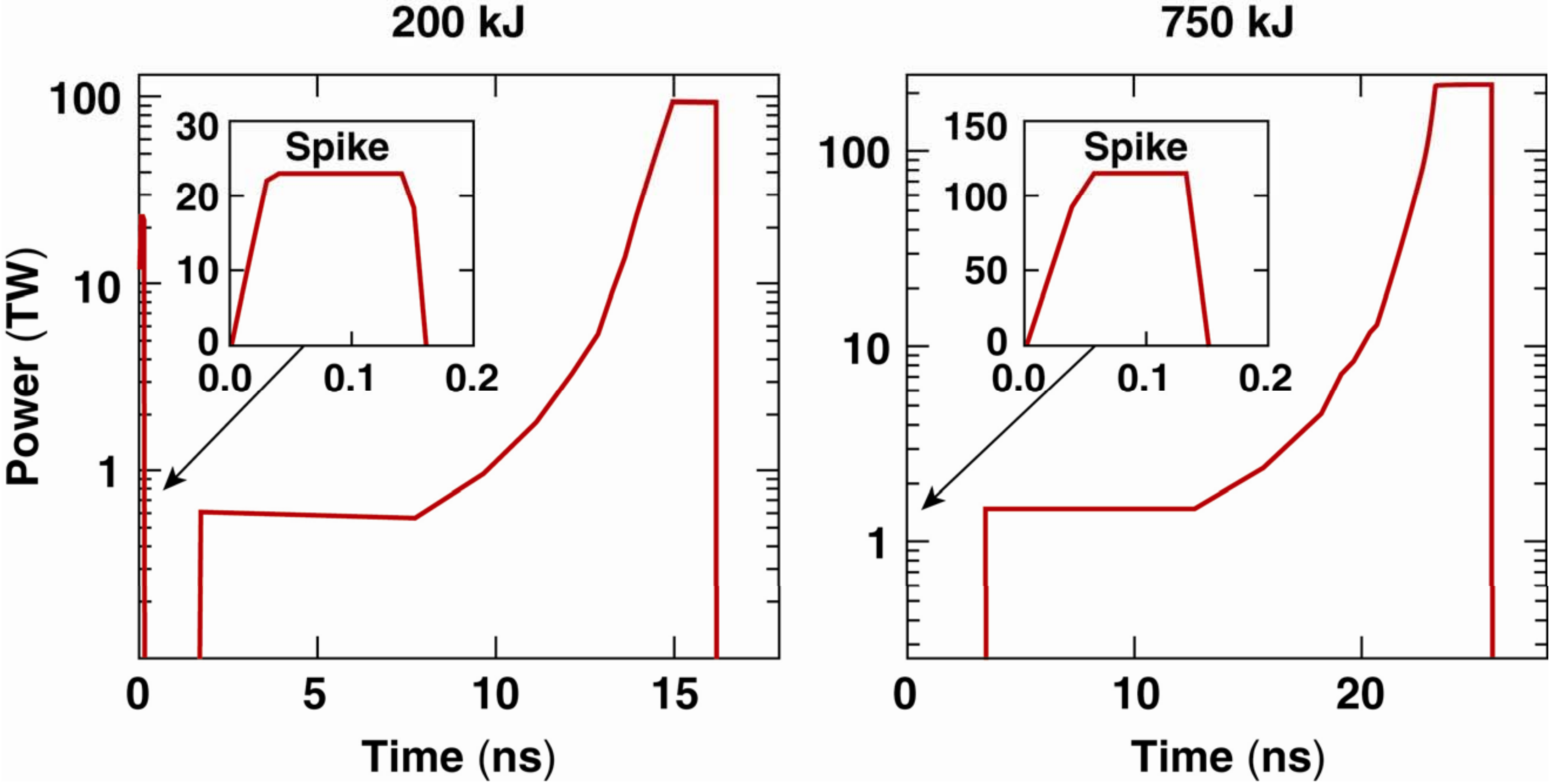
# Optimized fast-ignition cryo-targets are thick shells of wetted foam with initial aspect ratio ~2



R. Betti, A .Solodov, J. Delettrez, C. Zhou, Phys. Plasmas (submitted)

TC7378

# Fast-ignition targets require long laser pulses and high contrast ratios (~100 to 150) within the capabilities of the NIF



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

# Optimized fast-ignition implosions are NOT affected by the Rayleigh–Taylor instability

- Number of *e*-folds for the most dangerous RT modes

$$\mathrm{Ne}_{k\Delta=1} \approx \frac{6V_i(cm/s)}{3 \bullet 10^7}\left[\frac{1}{<\alpha>^{0.3}} - 0.08\left(\frac{\alpha_{outer}}{<\alpha>}\right)^{0.6}\right]$$

$$V_i \approx 1.7 \bullet 10^7$$

$$\alpha_{inner} \approx 0.7$$

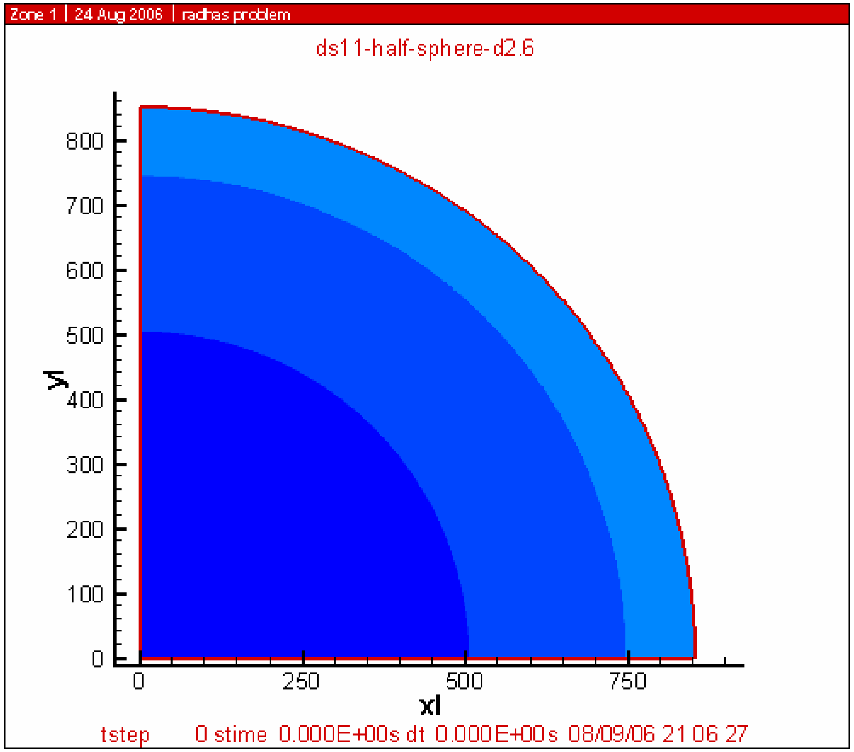
$$\alpha_{outer} \approx 2$$

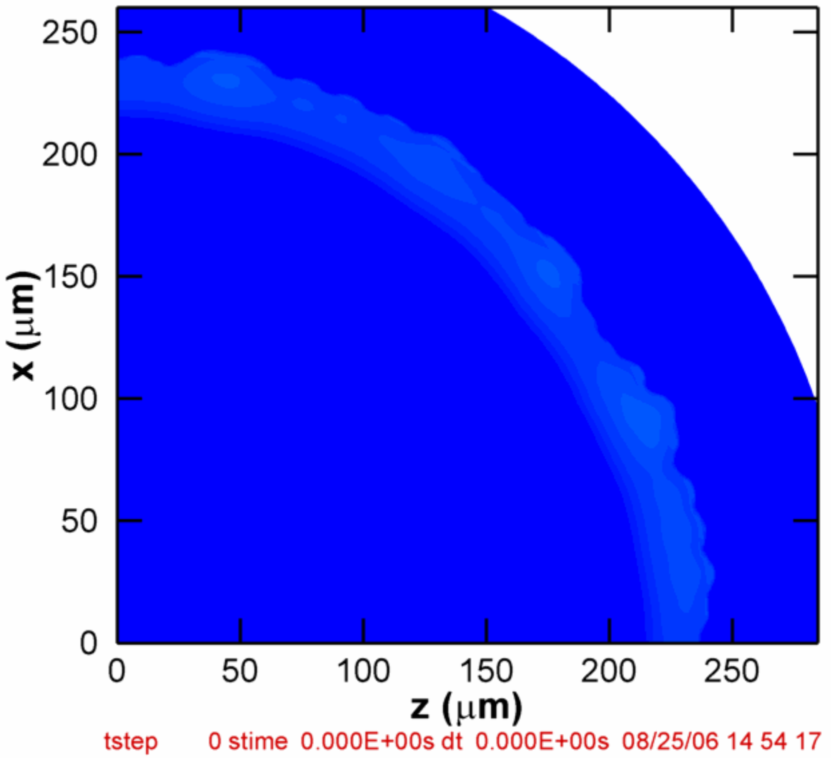
→

$$Ne_{k\Delta=1} \approx 3$$

# 2-D multimode simulations of a 250 kJ fast-ignition target implosion show little RT growth

**Laser imprinting, Modes $\ell = 4$ to 100, 1-THZ SSD, $E_L = 250$ kJ,**
**$V = 2 \cdot 10^7$ cm/s, $\alpha = 0.7$, IFAR = 21**

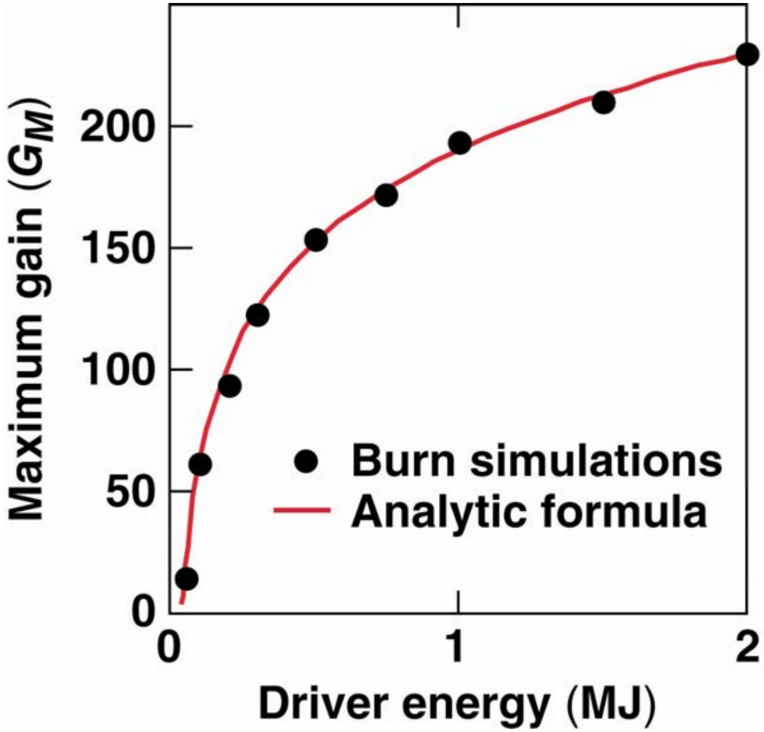


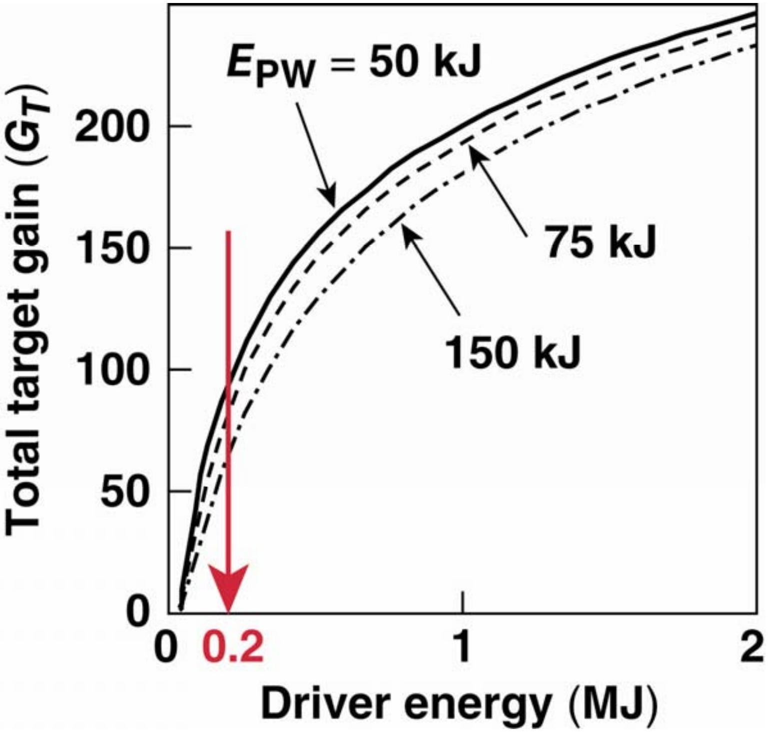


# High gains are possible with small drivers with energy as low as 200 kJ

$$G_M = \frac{E_{\mathrm{Fusion}}}{E_{\mathrm{Driver}}}$$

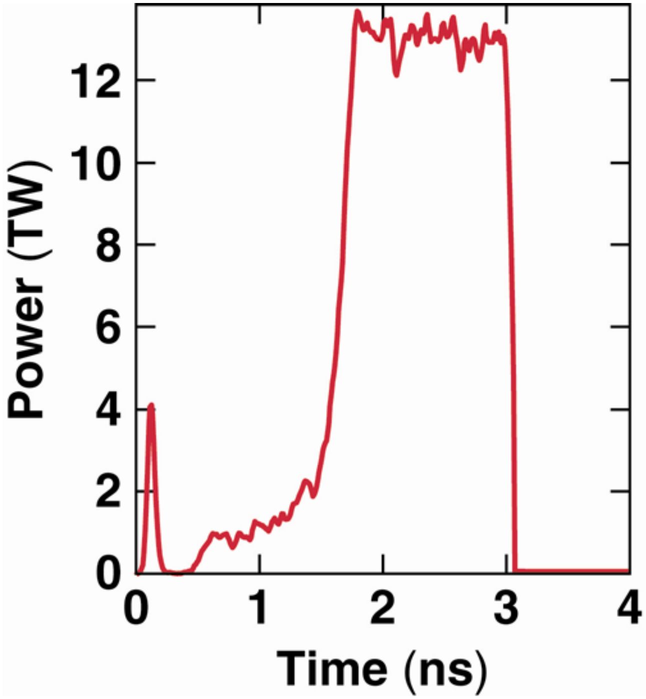
$$G_T = \frac{E_{\mathrm{Fusion}}}{E_{\mathrm{Driver}} + E_{\mathrm{Petawatt}}}$$

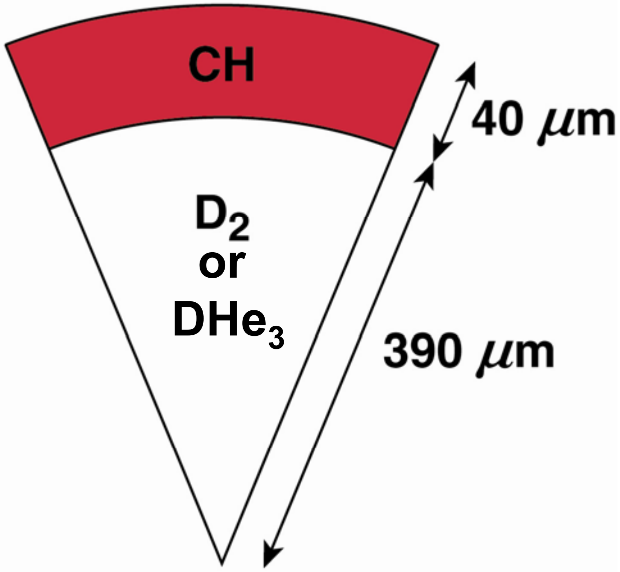




R. Betti, A .Solodov, J. Delettrez, C. Zhou, Phys. Plasmas (submitted)

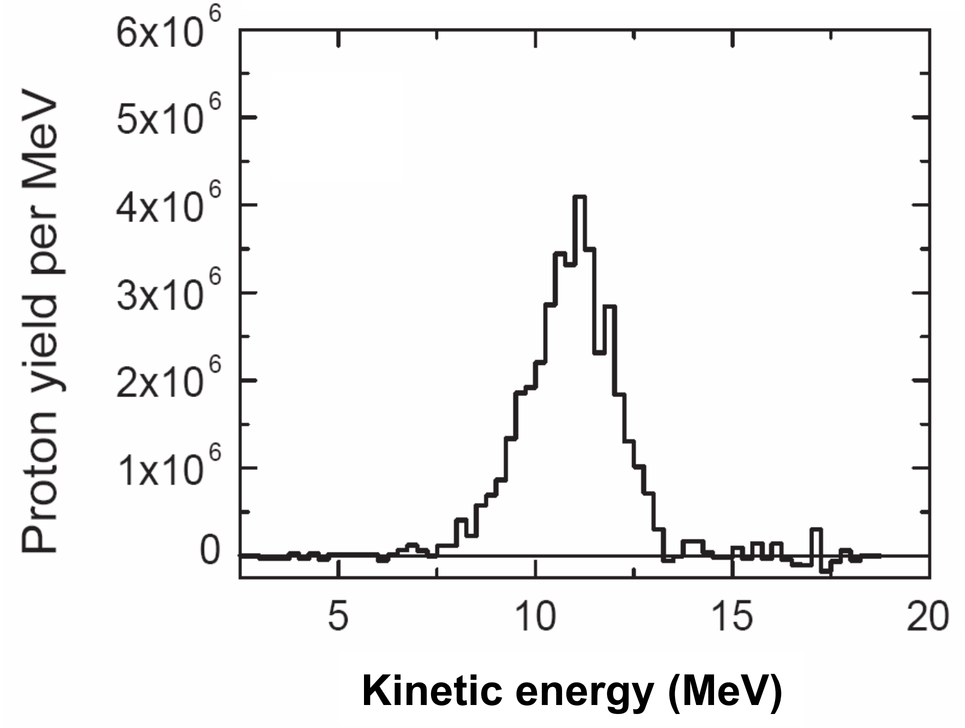
# Low-adiabat, low-$V_i$ implosions of CH targets are used to study fast-ignition fuel assemblies



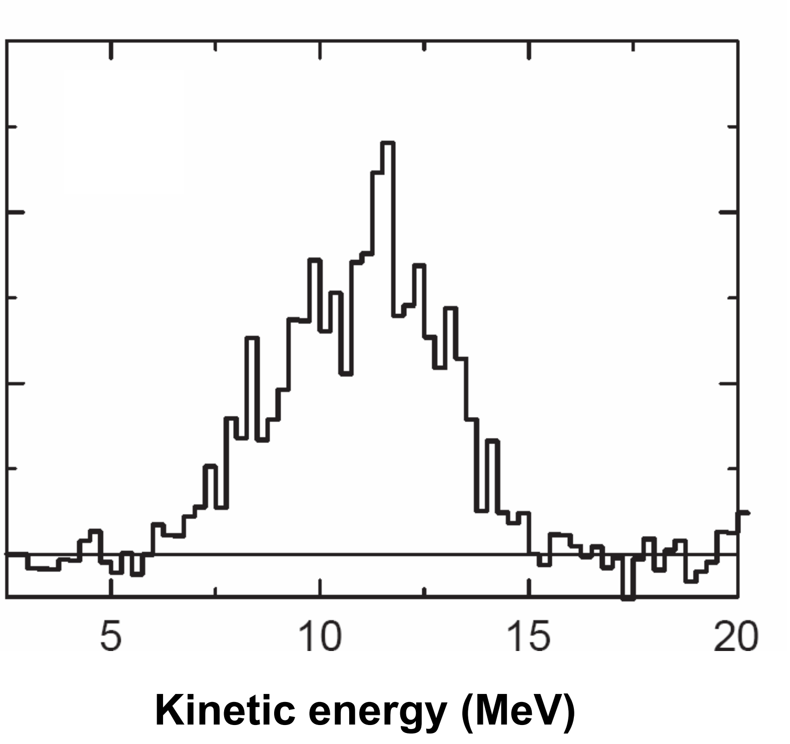


$\alpha \approx$ **1.3,** $V_i \approx$ **2 • $10^7$ cm/s**

# Well defined downshifted proton spectra are measured for both D2 and DHe3 gas fills

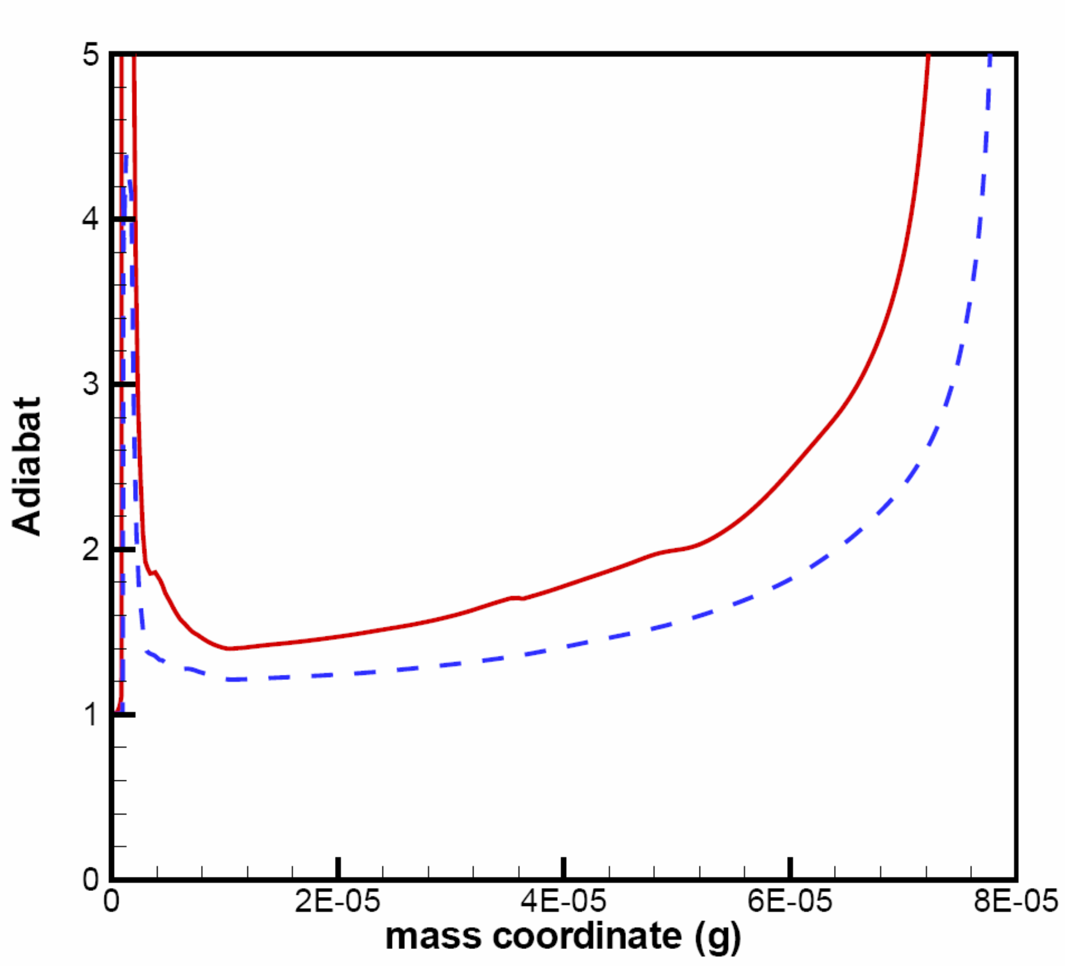


**DHe3 fill**



**DD fill**

# The shell adiabat is expected to be close to the design value



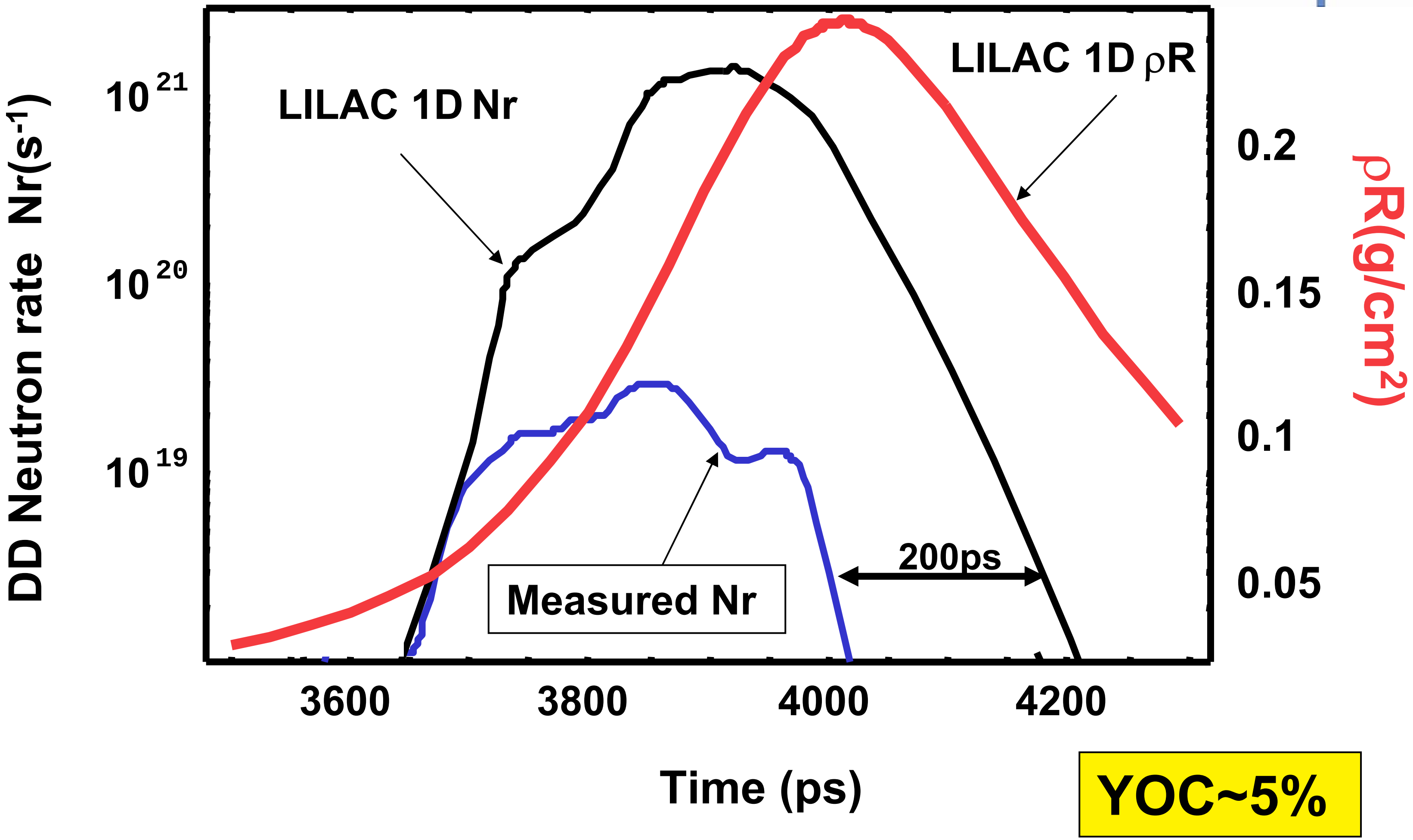
▬▬▬

**Adiabat simulated with the experimental laser pulse**

▬ ▬ ▬

**Adiabat simulated with the design laser pulse**

# The DD burn begins as predicted and shows a 200ps truncation probably due to hot spot CH-DD mixing

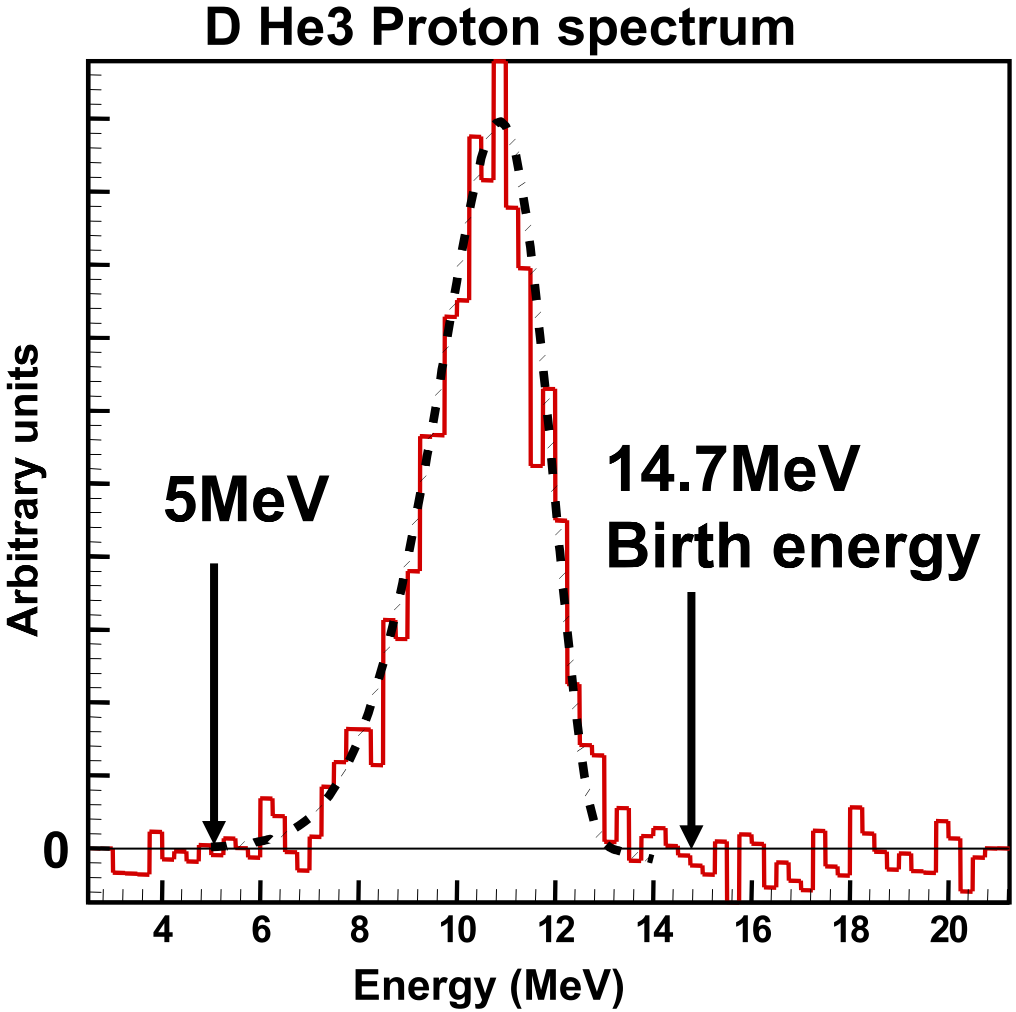


**YOC~5%**

# For the DD shots, the measured $\rho R$ is compared with the simulated $\rho R$ averaged over the measured neutron rate.

| Shot Number | Gas fill | Pressure (atm) | Measured Burn-averaged $\rho R$(g/cm2) | Simulated Burn-averaged $\rho R$(g/cm2) |
|---|---|---|---|---|
| 43074 | D2 | 34 | 0.133 | 0.138 |
| 43075 | D2 | 25 | 0.146 | 0.144 |
| 43107 | D2 | 25 | 0.122 | 0.132 |
| 43114 | D2 | 25 | 0.128 | 0.112 |
| 43106 | D2 | 13 | 0.128 | No NTD avail |
| 43108 | D2 | 13 | 0.129 | No NTD avail |
| 43109 + 43112 | D3He | 33 | 0.128 | No NTD avail |
| 43113 + 43113 | D3He | 25 | 0.130 | No NTD avail |
| AVERAGE | | | 0.131 | 0.130 |

# The maximum ρR during the burn can be inferred from the downshift of the tail of the proton spectrum



9.7MeV ΔE

\-

1.5MeV *

broadening

=

8.2 MeV

downshift

$$\left(\rho R\right)_{\max}^{burn} \approx 0.25 g/cm^2$$

* V. Smalyuk et al, Phy. Rev. Lett. 90, 135002-1, (2003)

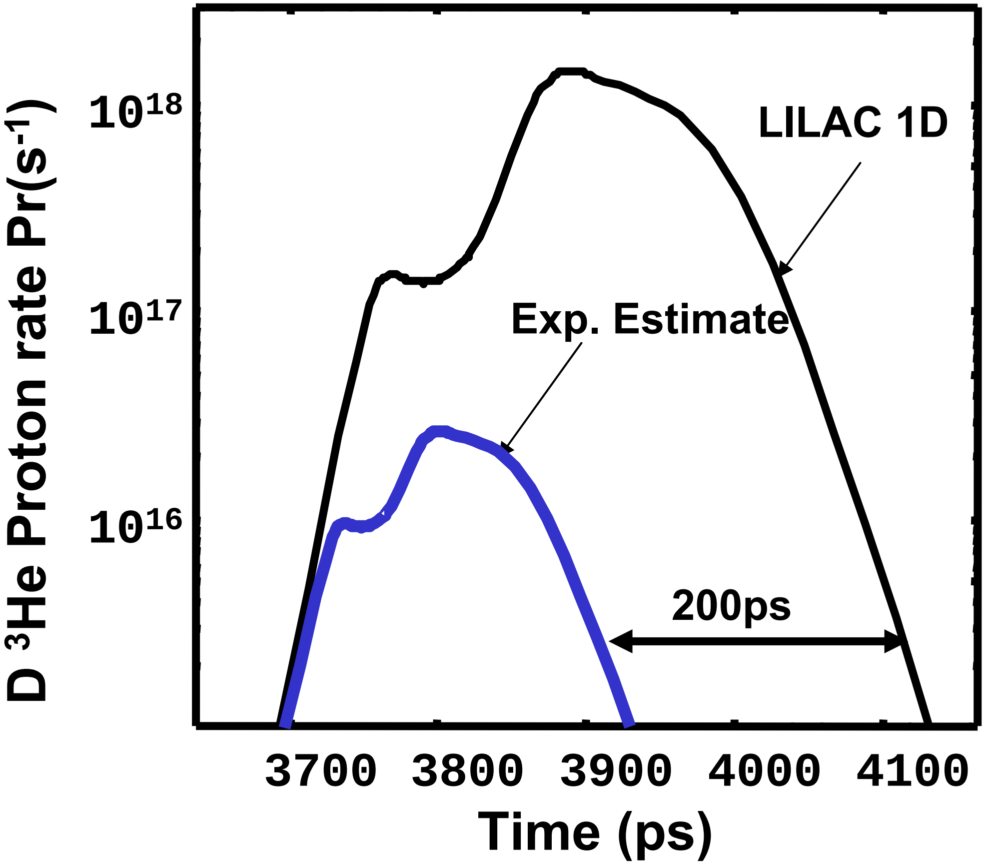
# The measured maximum $\rho$R during the burn agrees with the 1D predictions

| Maximum $\rho R$ during burn | Measured ($g/cm^2$) | Simulation ($g/cm^2$) |
|---|---|---|
| $\rho R_{max}$<br>$DHe_3$ fill, 33 atm.<br>Averaged over 43109-43112 | 0.238 | 0.246 |
| $\rho R_{max}$<br>$DHe_3$ fill, 25 atm.<br>Averaged over 43110-43113 | 0.244 | 0.264 |

→This assembly can stop 3MeV electrons for 2$\rho$R.

→Simulations show that empty shells reach $0.5 g/cm^2$ and can stop up to 5MeV electrons for 2$\rho$R.

# The D-He3 proton rate is estimated based on the rise time and the measured 200ps truncation



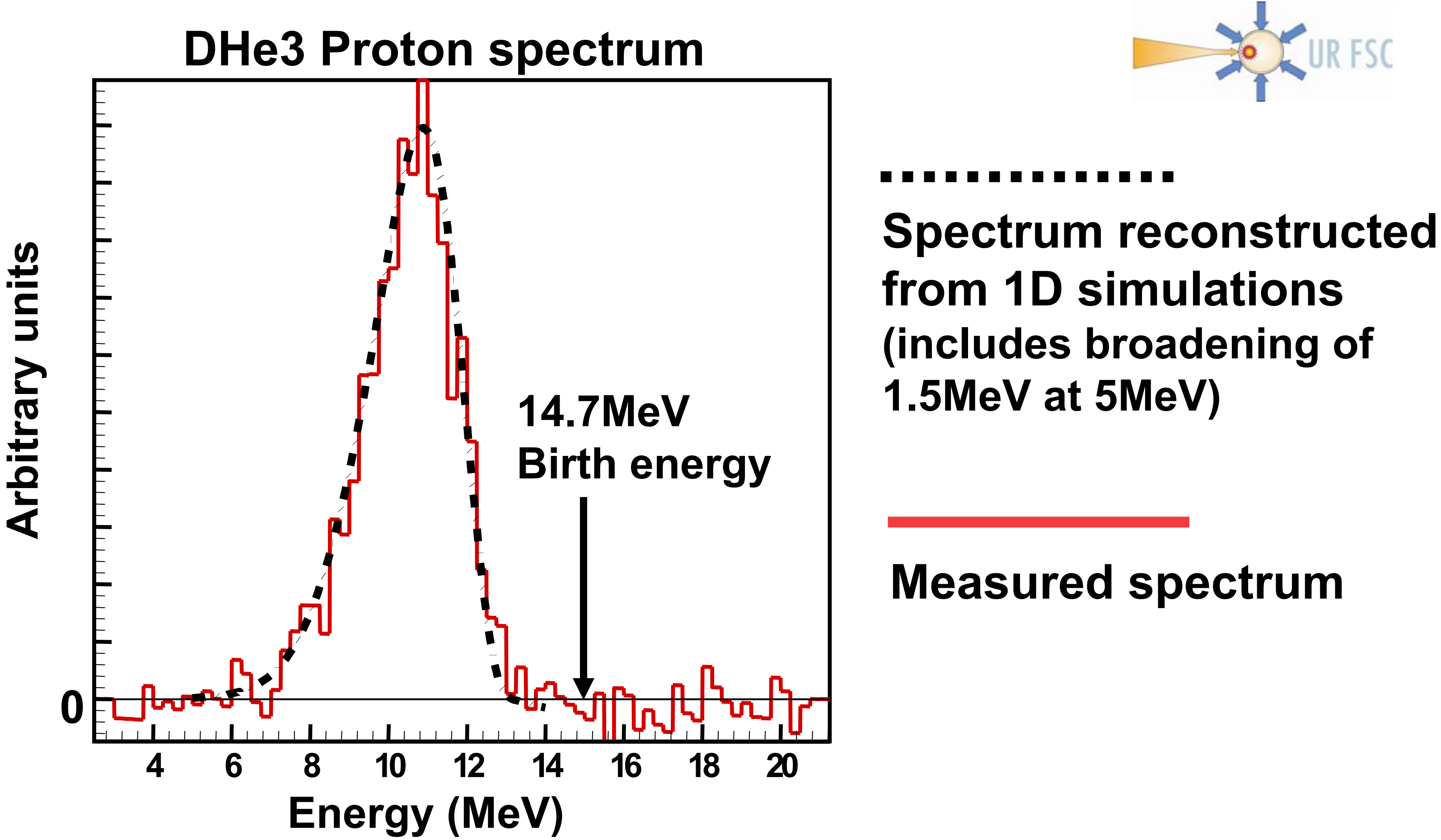
**A from $Y_p$=3% of 1D**

**$t_0$(ns) from 1D rise time**

**ξ from 200ps burn truncation**

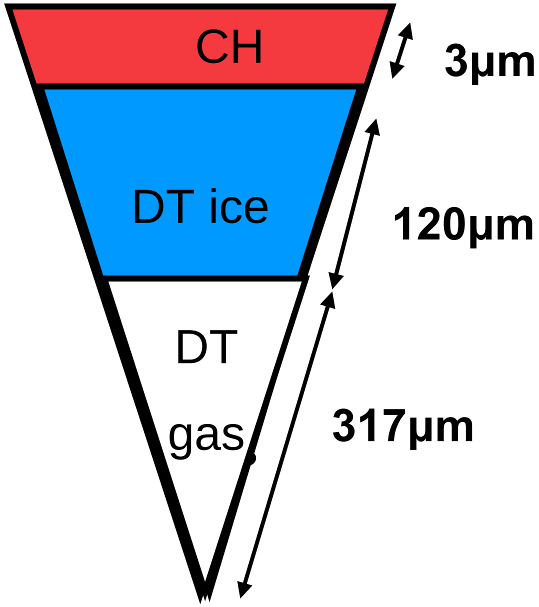
$$\mathrm{Pr}_{\exp}^{estimate} = A \bullet \mathrm{Pr}_{1D}^{LILAC}\left[\frac{t - t_0 - 3.9}{\xi} - 3.9\right]$$

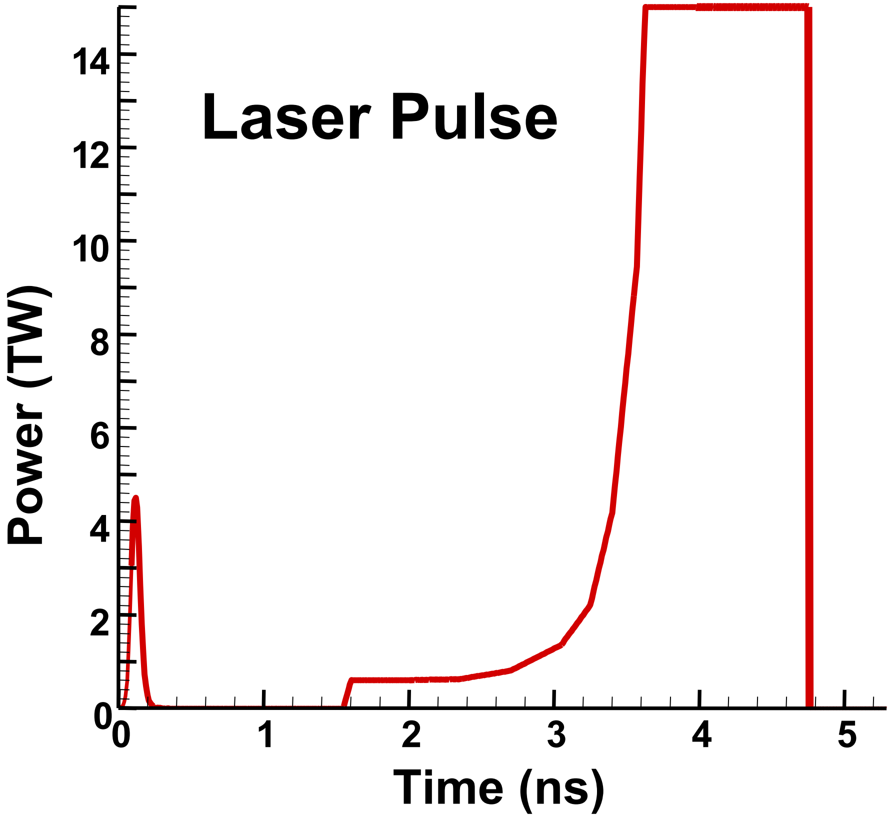
# Using the estimated proton rate and the simulated $\rho R$, the downshifted proton spectrum is constructed and compared with the measured spectrum



**The good agreement suggest that the simulated time evolution of the areal density is correct**

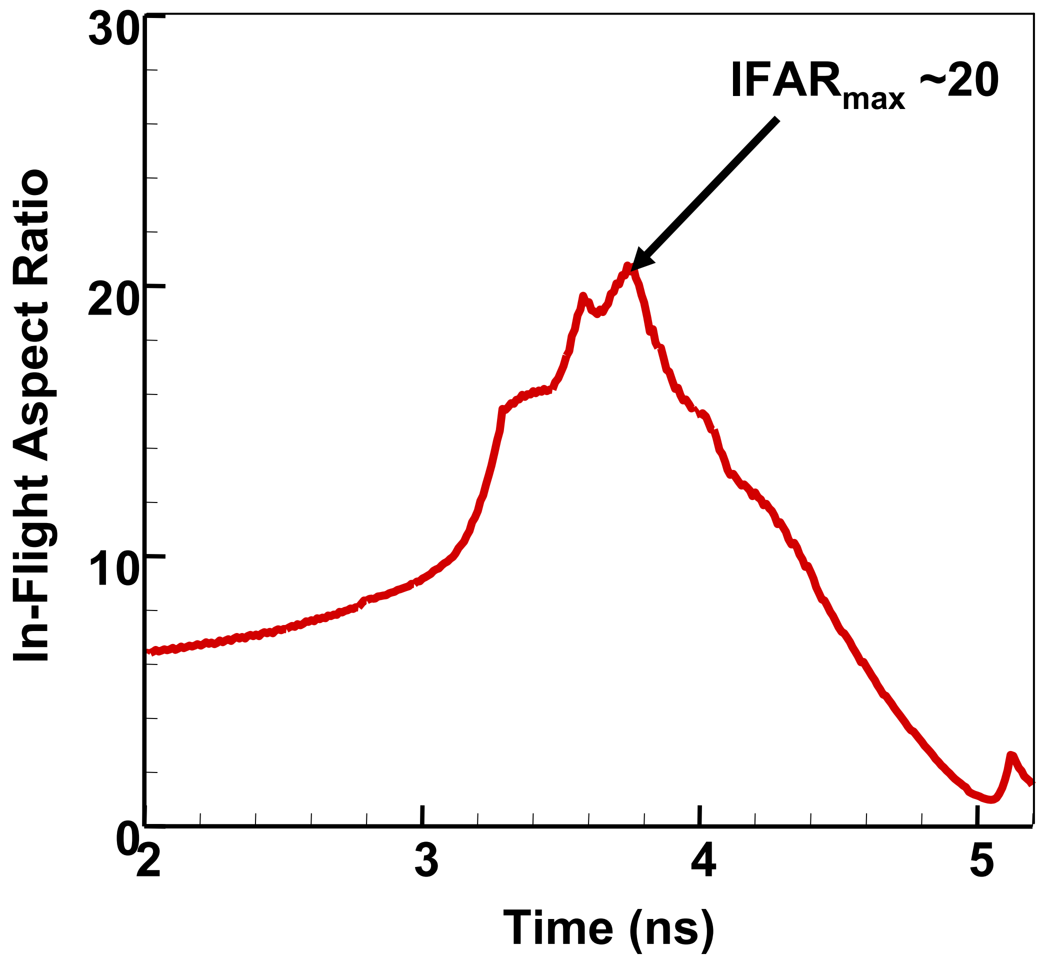
# High-ρR Fast-Ignition 20kJ OMEGA cryo-DT implosions are designed with a low velocity and low adiabat (~1)



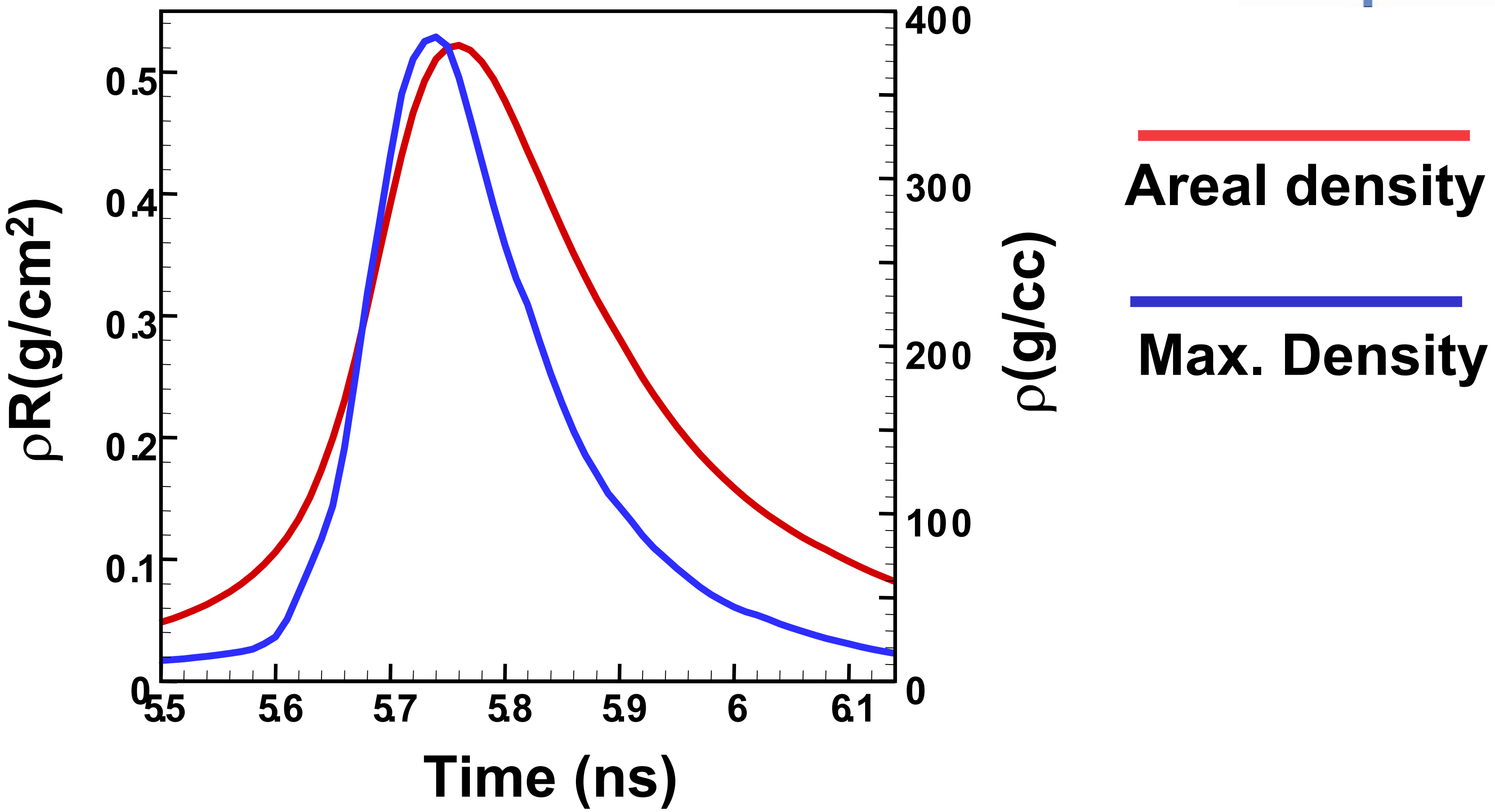


**$E_L$=20kJ**
**α=1.3**
**N-yield = 7e12**

# The in-flight aspect ratio is low ~ 20 leading to 3 e-folding of RT growth



# The simulated areal density exceeds 0.5 g/cm$^2$ and the density reaches 1700 X solid density



# Fuel assembly experiments on OMEGA indicate that high areal densities can be reached with slow low-adiabat implosions

- A gain formula for FI based on constrained optimization of the target design is derived and compared with 2D simulations of the ignition and burn

- Neutron averaged areal densities of 130-140mg/cm$^2$ have been measured from the average downshift of the primary and secondary proton spectra

- The maximum areal density during the burn inferred from the tail of the primary proton spectra reaches ~240mg/cm$^2$ in agreement with 1D simulations

- OMEGA size FI cryo targets are designed to reach areal densities above 500mg/cm$^2$ and peak densities of 380g/cc