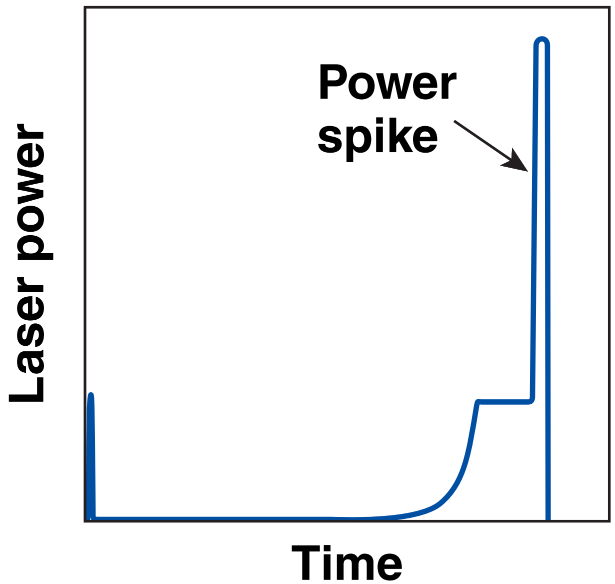
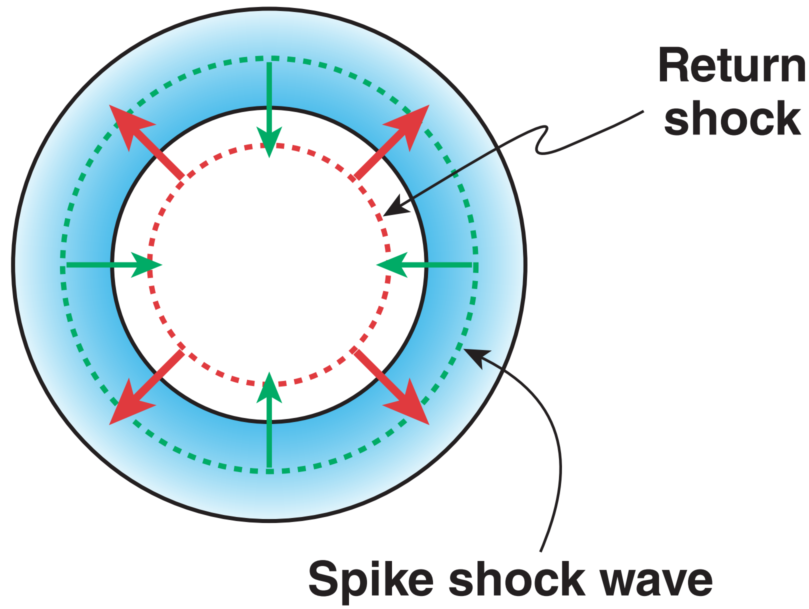
OMEGA Experiments on the Shock-Ignition ICF Concept





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Division of Plasma Physics
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Summary

The first experimental results of the shock-ignition concept show significant improvement in performance

- Direct-drive shock ignition promises ~3 times lower driver energy for hydro-equivalent high-gain targets than the conventional ICF concept.
- Systematic studies of low-adiabat ($\alpha \approx 1.5$), warm-plastic-shell implosions were performed on OMEGA with short-picket and high-intensity spike pulses.
- The spike shock-generated CH-shell implosion showed a factor of ~4 enhanced fusion-product yields and higher $\langle \rho R \rangle \sim 0.2$ g/cm^2 indicating a higher compression and better stability.
- Initial shock-ignition experiments with cryogenic D_2 and DT targets were performed showing ~1-D–like fuel assembly and up to 12% yield-over-clean.

Collaborators

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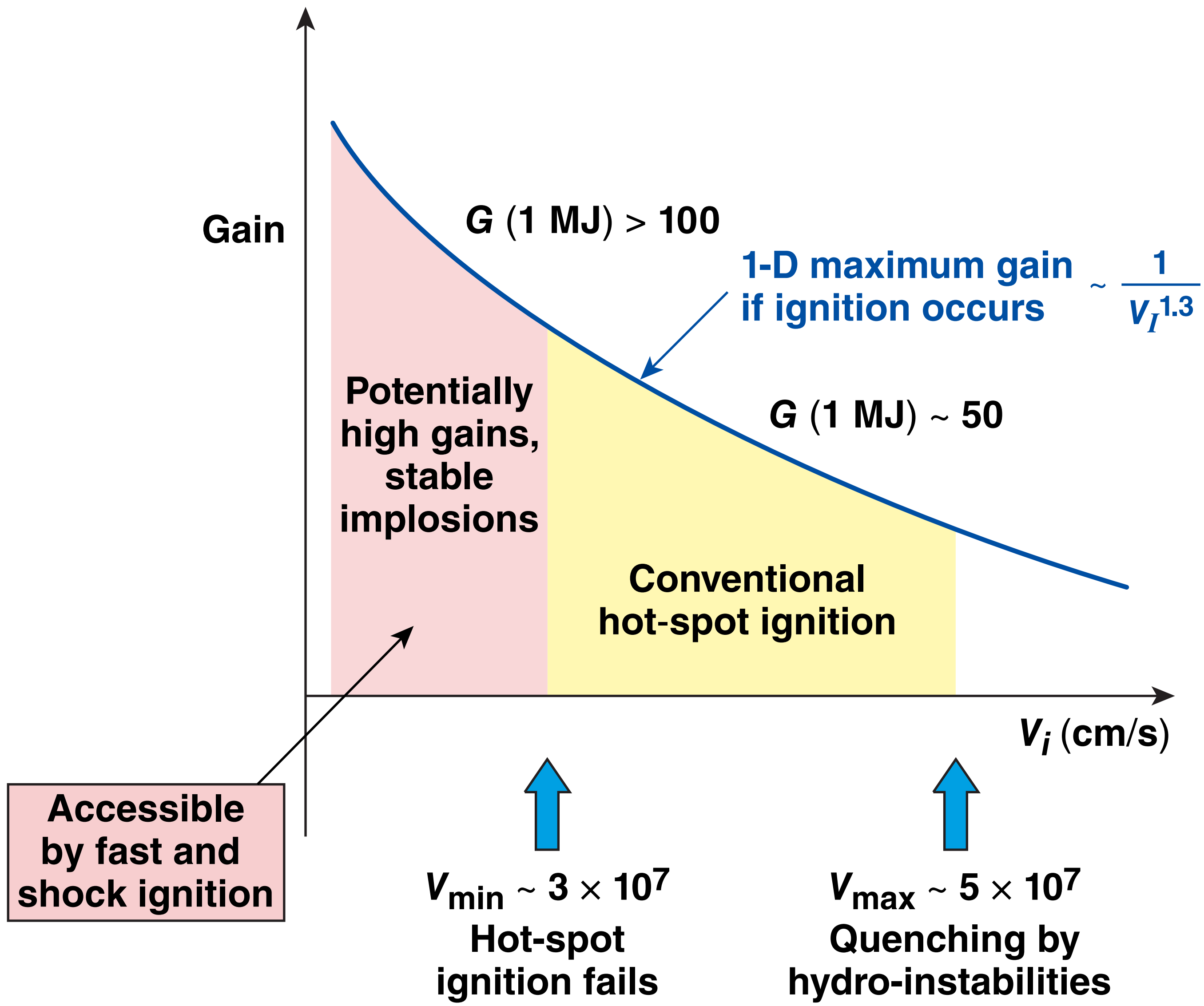
Fast and shock ignition can trigger ignition in massive (slow) targets leading to high gains

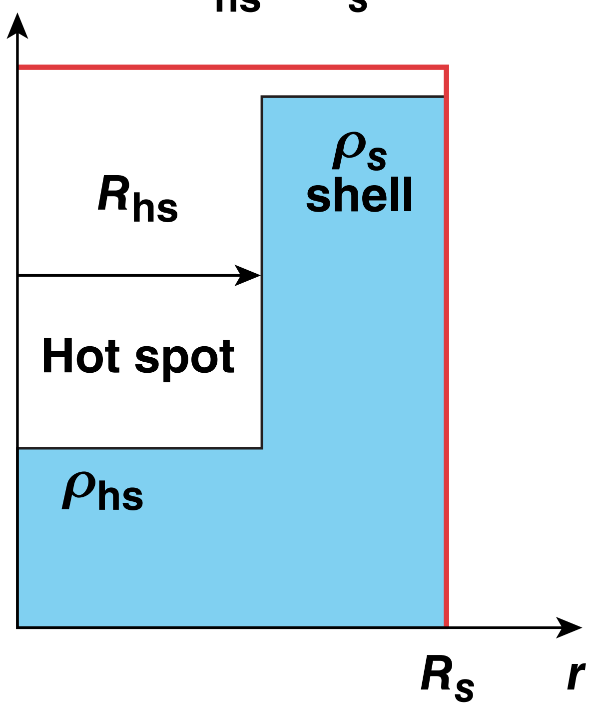


TC7815b

The energy required for isobaric ignition depends on implosion velocity and adiabat

Isobaric fuel assembly

$P = P_{hs} = P_s$



$$\alpha = \frac{P_{\text{plasma, shell}}}{P_{\text{Fermi}}} = \text{shell adiabat}$$

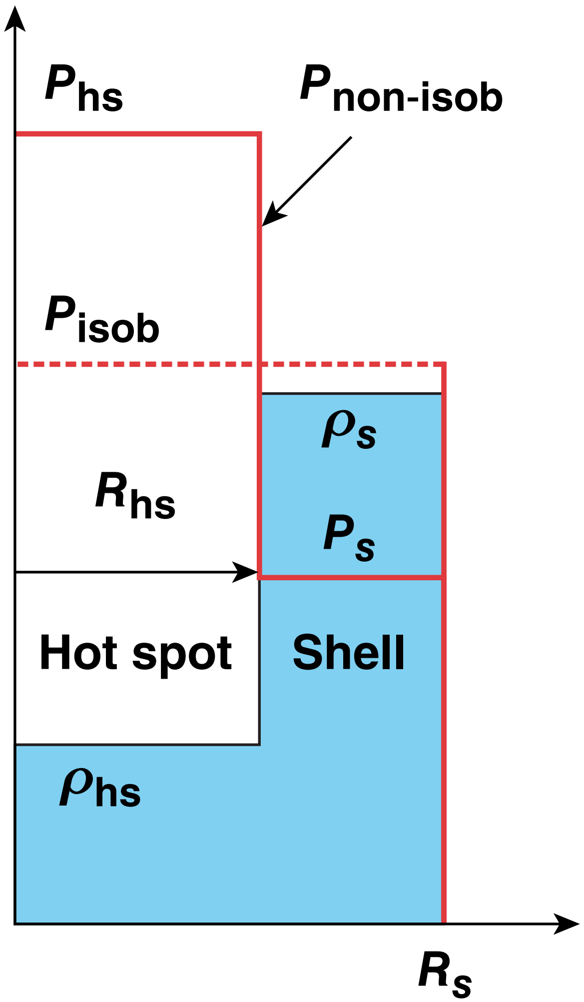
V_i = implosion velocity

Laser-energy scaling for direct-drive isobaric ignition

$$E_{\text{Laser}}^{\text{isob–ign*}} \sim \frac{\alpha^{1.8}}{V_i^{\,6}}$$

*M. C. Herrmann, M. Tabak, and J. D. Lindl, Phys. Plasmas 8, 2296 (2001).

The ignition condition is more favorable for a non-isobaric fuel assembly with a peaked pressure*



$$E_{Laser}^{non\text{-}isob-ign} \sim \frac{E_{Laser}^{isob-ign}}{\Phi}$$

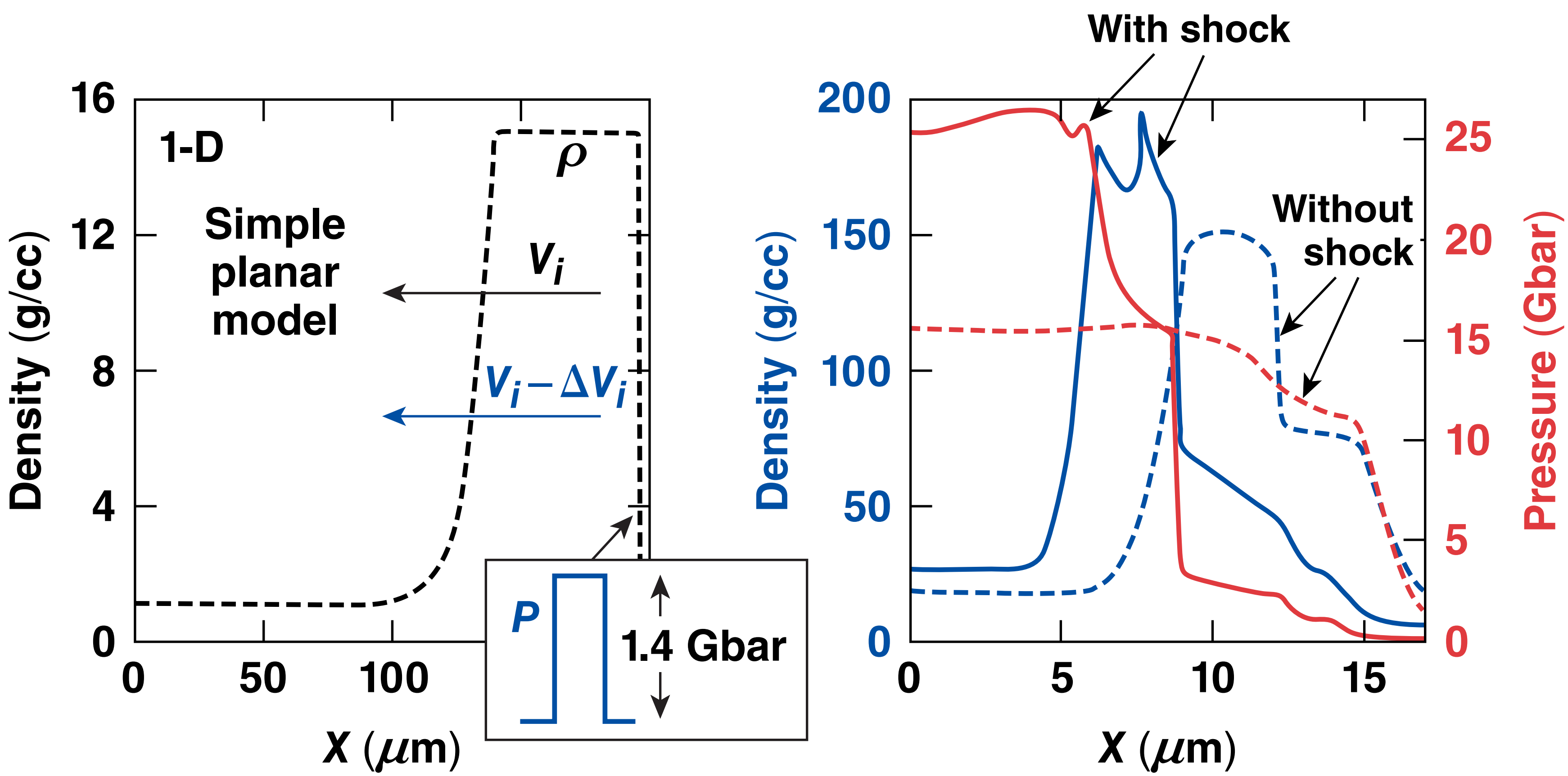
For adiabatic compression of the hot spot

$$\Phi \approx \left(\frac{P_{hs}}{P_{iso}}\right)^{2.5}$$

TC7819

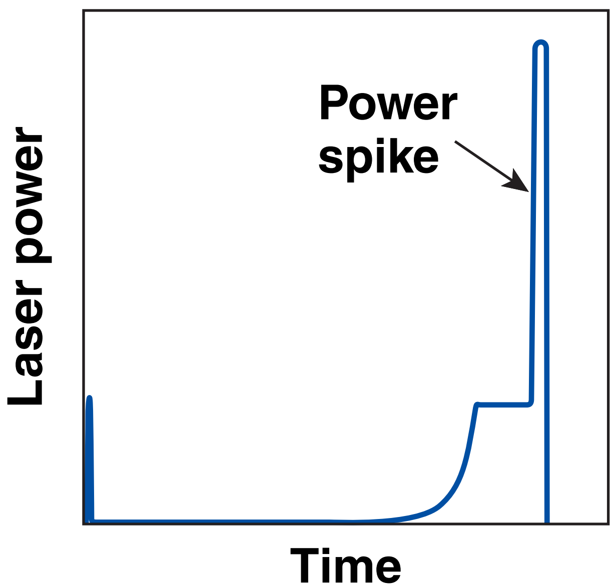
*R. Betti *et al*., Phys. Rev. Lett. 98, 155001 (2007).

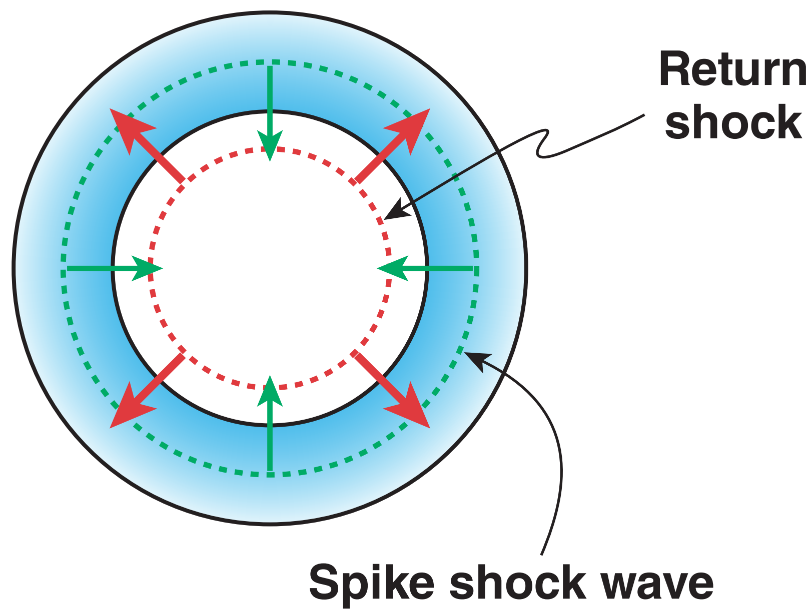
A non-isobaric fuel assembly can be produced by shocking the target just before peak compression



R. Betti *et al*., Phys. Rev. Lett. 98, 155001 (2007).

A shaped laser pulse with high intensity spike launches a strong shock wave for ignition





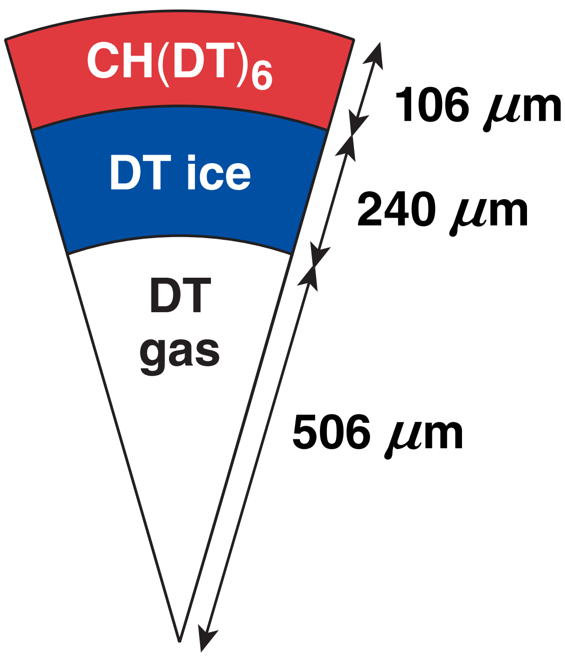
The ignitor shock wave significantly increases its strength as it propagates through the converging shell.

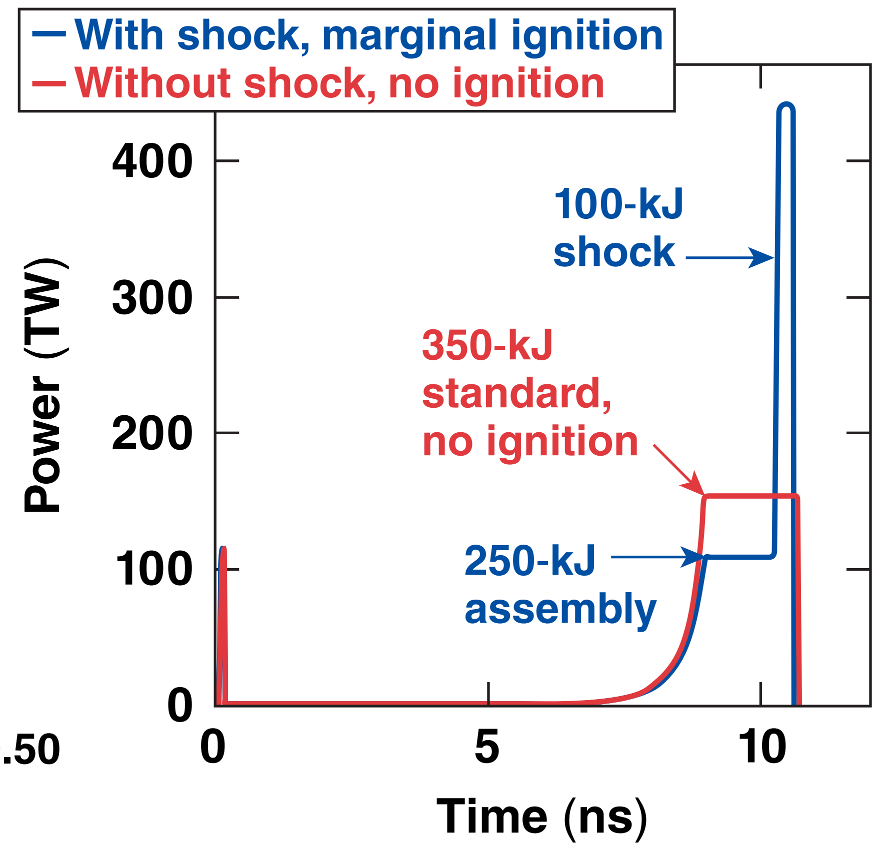
L. J. Perkins *et al*., (JO3.00014)
A. J. Schmitt *et al*., (PO6.00015)

E16323

1-D marginal shock ignition requires thick shells, low adiabats, and ~350 kJ of laser energy*

E_L = 350 kJ, $V_i = 2.4 \times 10^7$ cm/s, α = 1, λ_L = 0.35 μm



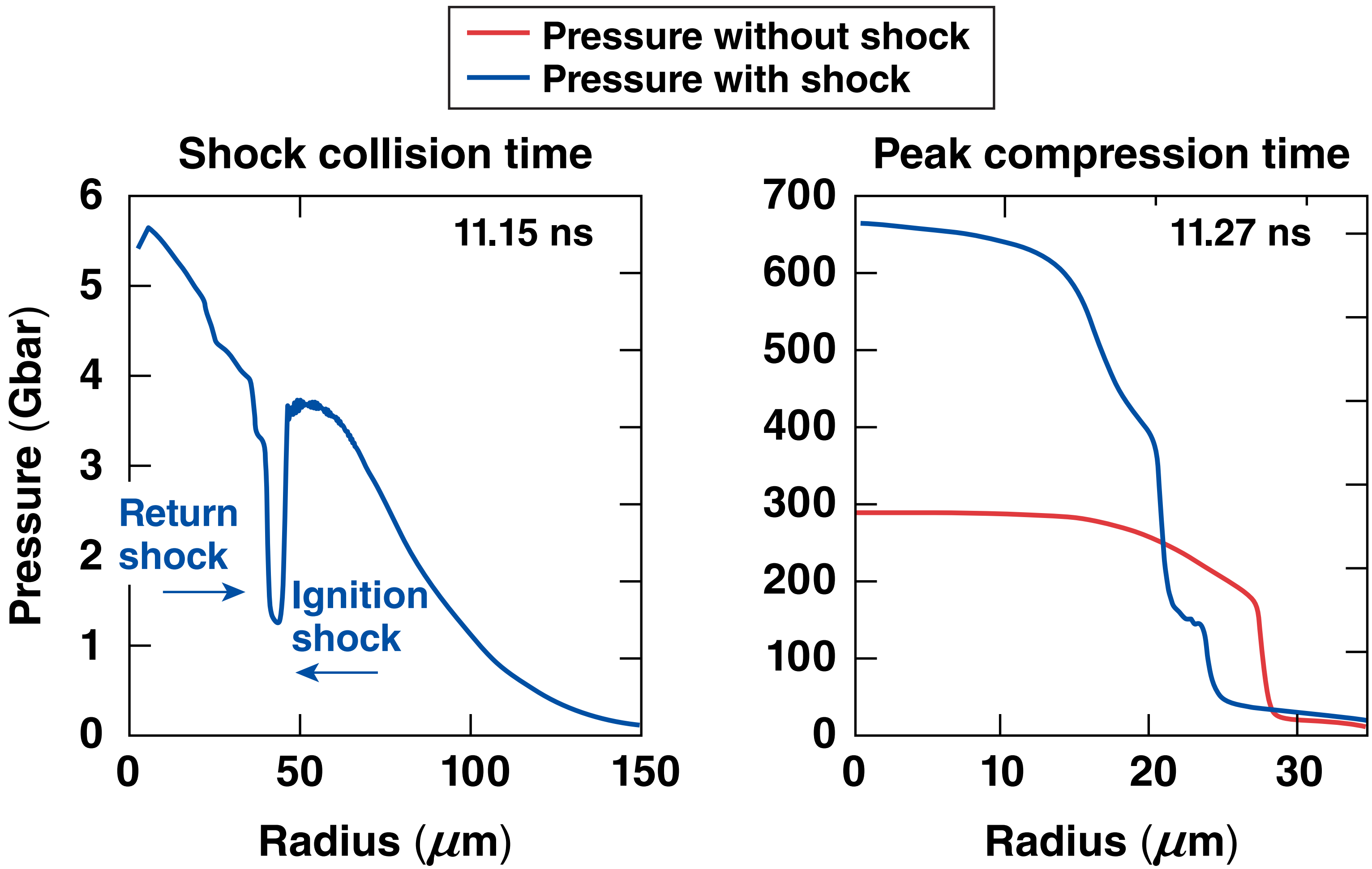


- Standard pulse shape abs. frac. = 0.55
- Shock-ignition pulse shape abs. frac. = 0.50

TC7821a

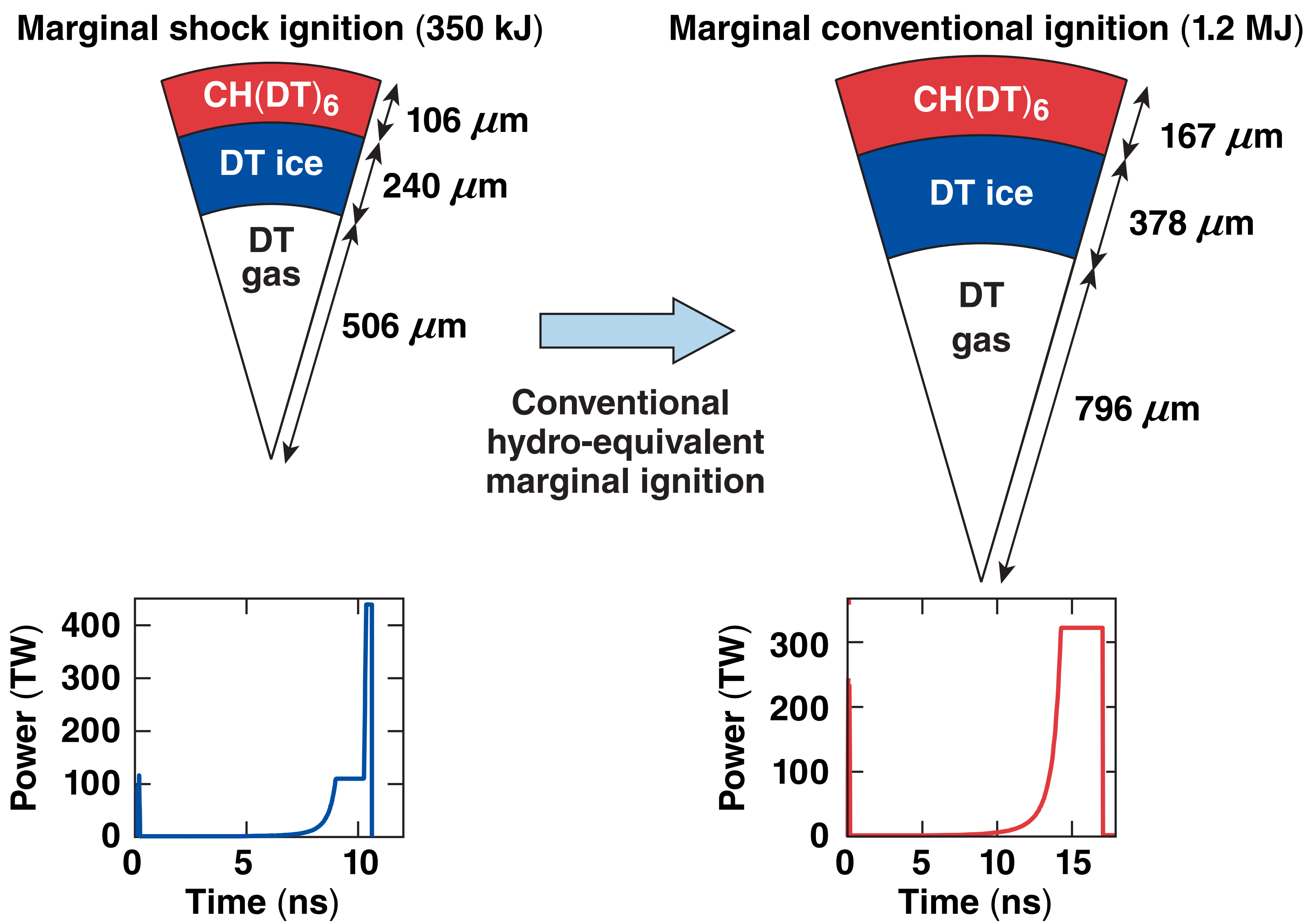
*R. Betti *et al*., IFSA proceedings (2007).

Shock-ignition pulse shapes lead to higher compression and more favorable ignition conditions



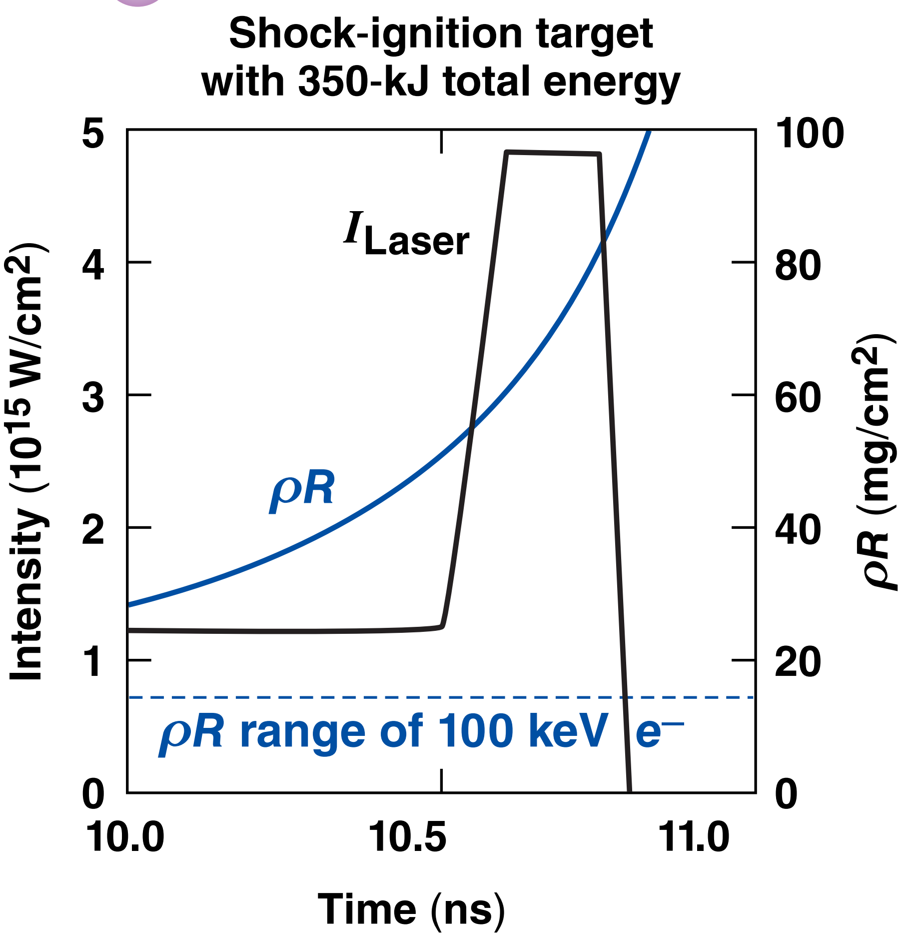
TC7868b

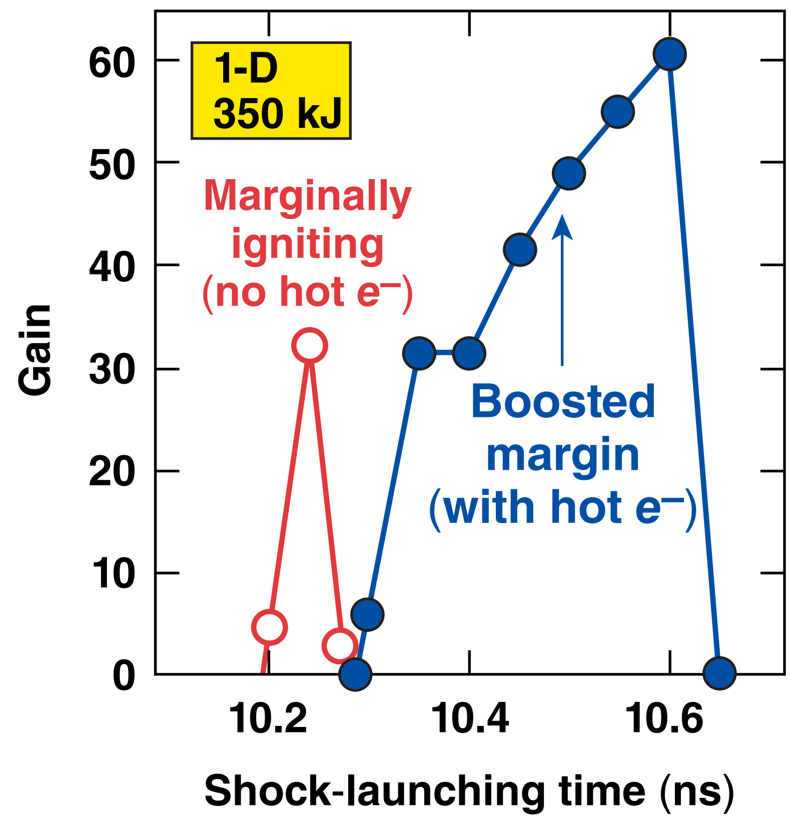
A hydrodynamic-equivalent conventional hot-spot isobaric target requires ~1.2 MJ to achieve marginal ignition



E16312

Hot electrons of moderate energies produced during the shock spike can be beneficial to shock ignition





Hot e⁻ with Maxwellian T_{hot} = 150 keV, E_{hot} = 17% of spike energy, treated using a multigroup diffusion model*

TC7870a

*J. Delettrez and E. B. Goldman, LLE, Univ. of Rochester, Rochester, NY, LLE Report No. 36 (1976).

Three major shock-ignition issues are addressed in OMEGA laser experiments

- It is studied how the impulsive acceleration created by the ignition shock wave affects the fuel assembly.

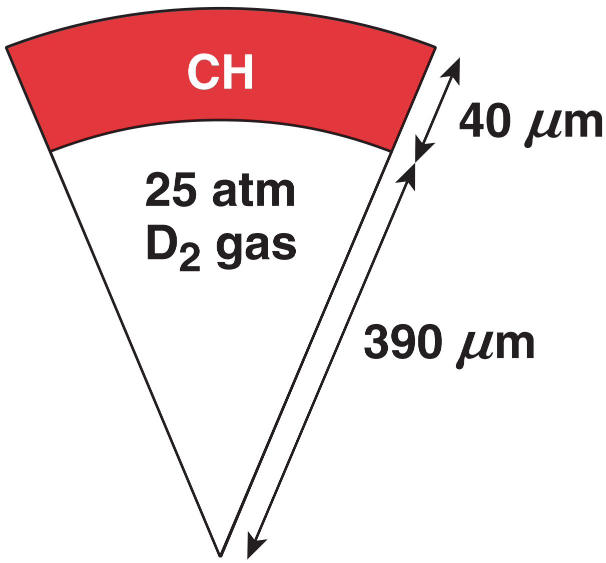
- Varying the timing of the peaks in the laser pulse shape is used to study the timing of the shock waves and to optimize the implosion.

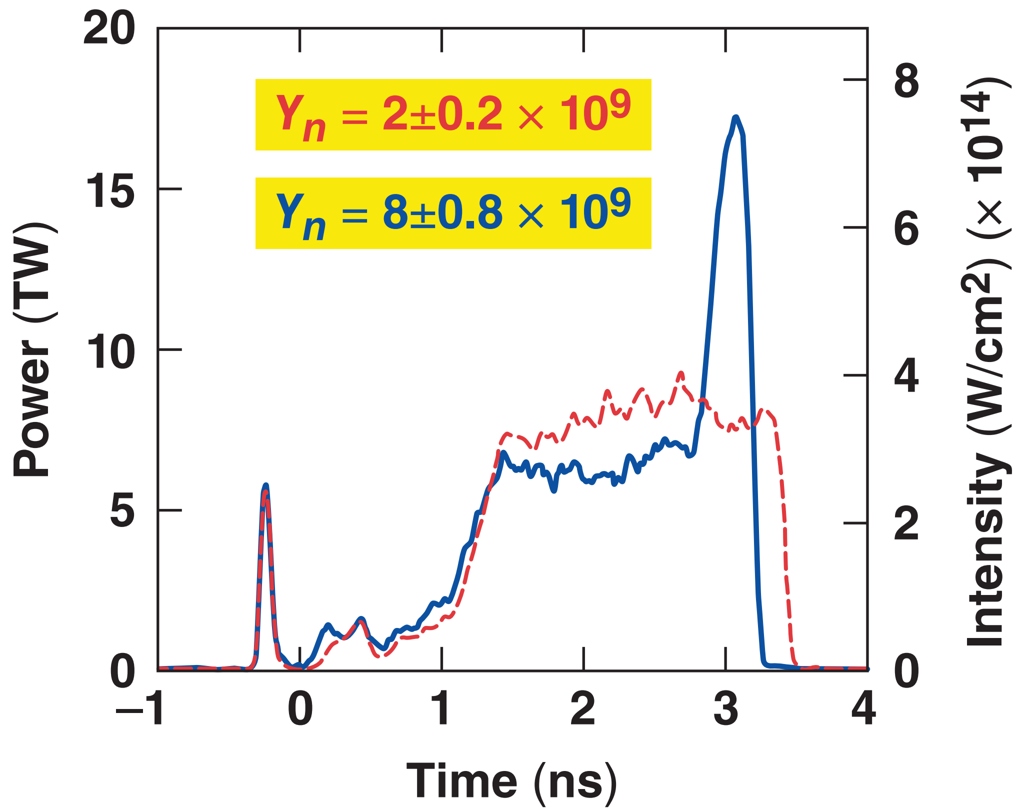
- Plastic-shell implosions were used to study how fuel–shell mixing affects the yield performance for shock-ignition pulse shapes.

- Only shocks with moderate strength can be launched at the end of the pulse on OMEGA.

CH shells have been imploded on OMEGA to test the performance of shock-ignition pulse shapes

E_L = 19 kJ, α = 1.3,
V_i = 1.7 × 10^7 cm/s, SSD off

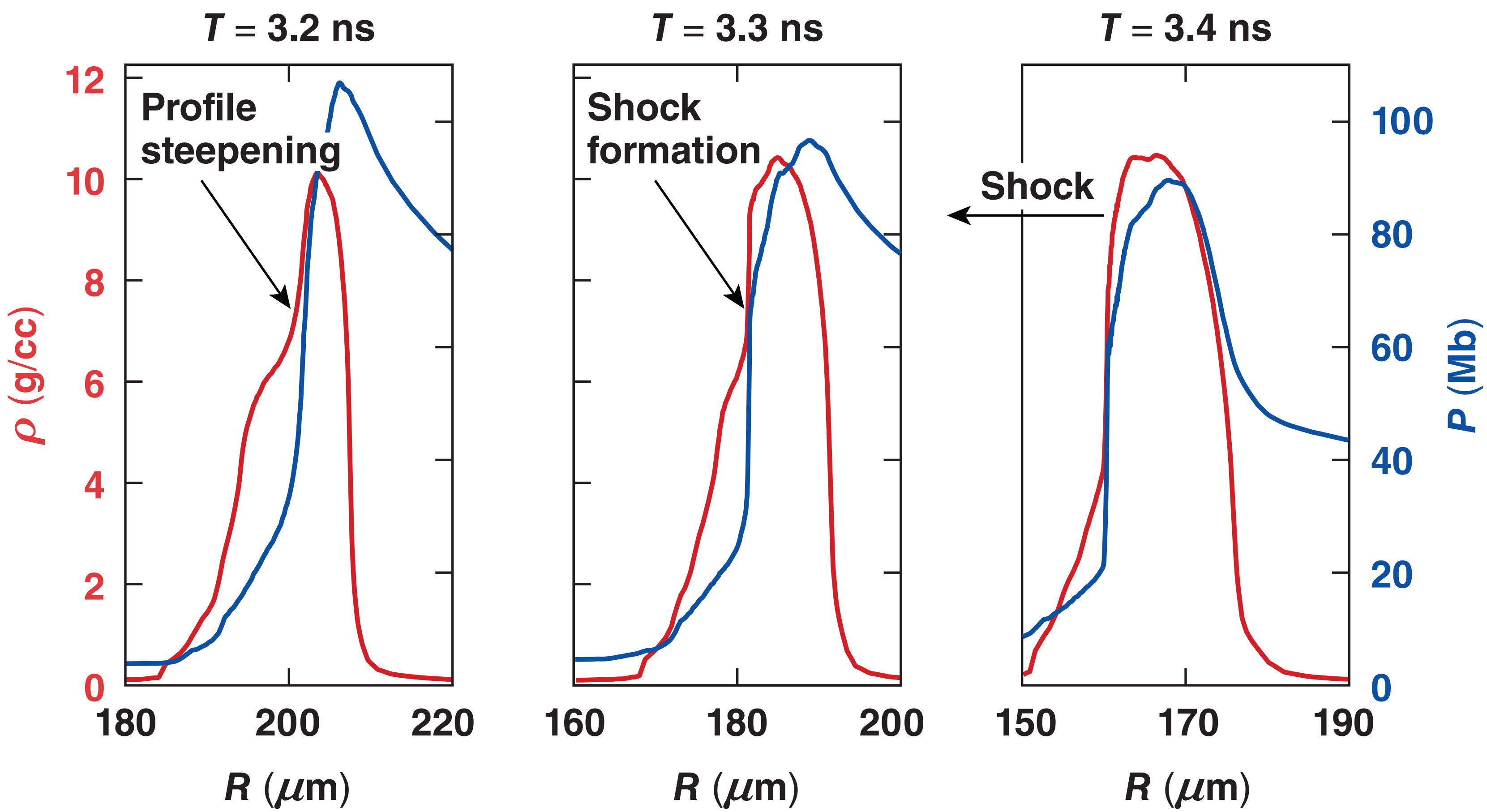




The neutron yield increases considerably when a shock is launched at the end of the pulse.

E16128

With the high-intensity spike pulse there is a shock wave driven into the capsule

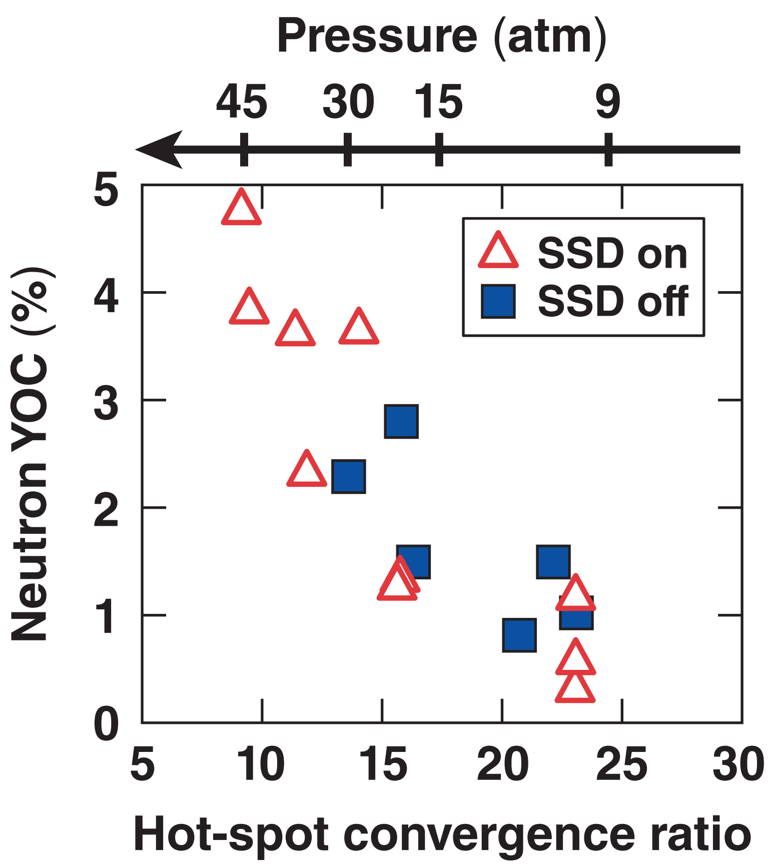


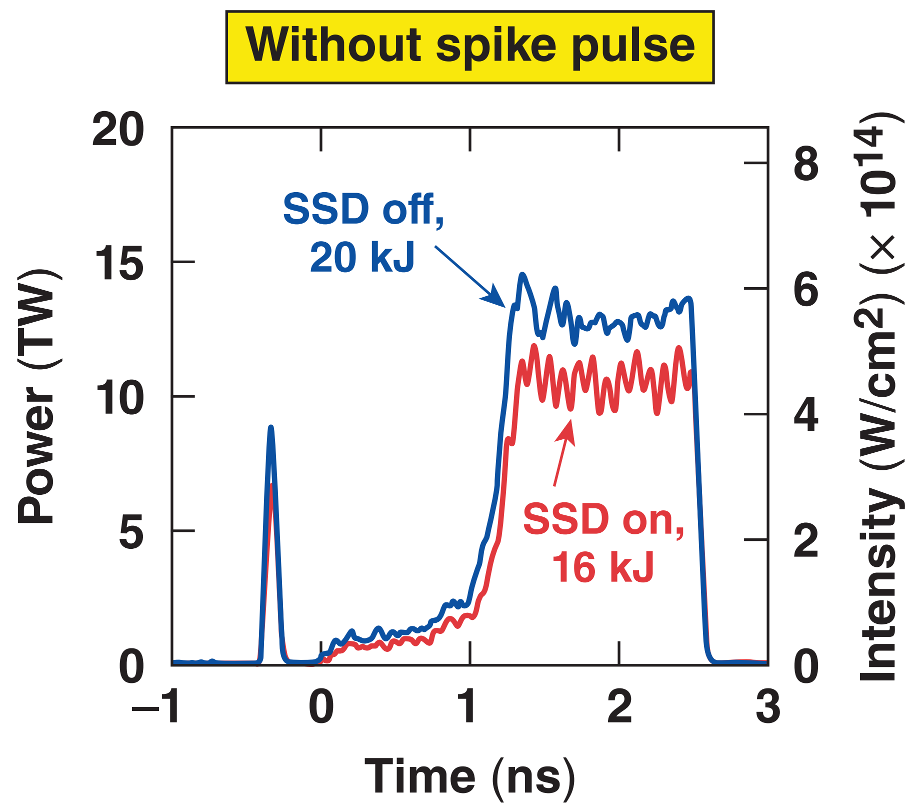
1-D *LILAC* hydrodynamic simulation for shot 46078 (25-atm D_2) shows the formation and evolution of the shock wave launched by the late spike.

E16313

No significant effect of SSD smoothing is observed in 40-μm shell, relaxation-picket, low-adiabat implosions

$$\text{Neutron YOC} = \frac{\text{Measured total yield}}{\text{1-D predicted yield}}$$





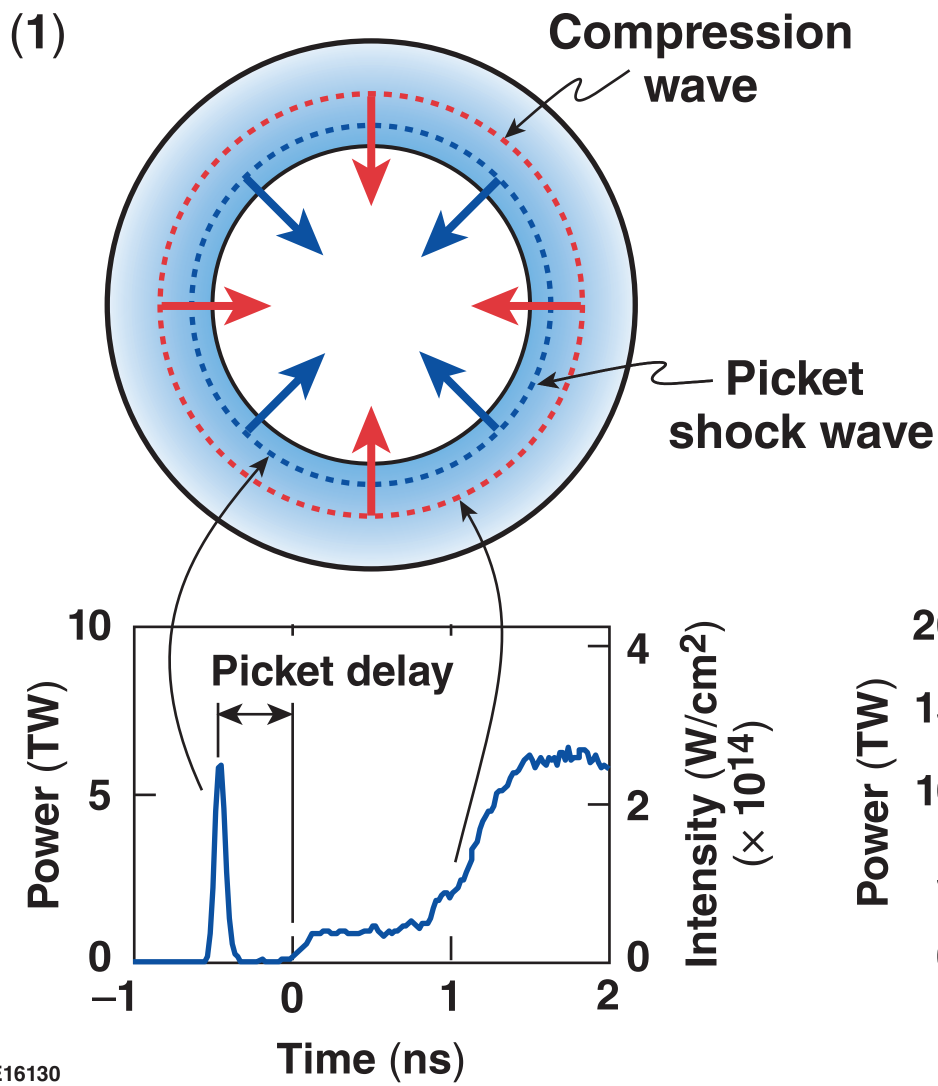
- With a high hot-spot convergence-ratio the fuel–shell mixing strongly quenches the fusion reactions.

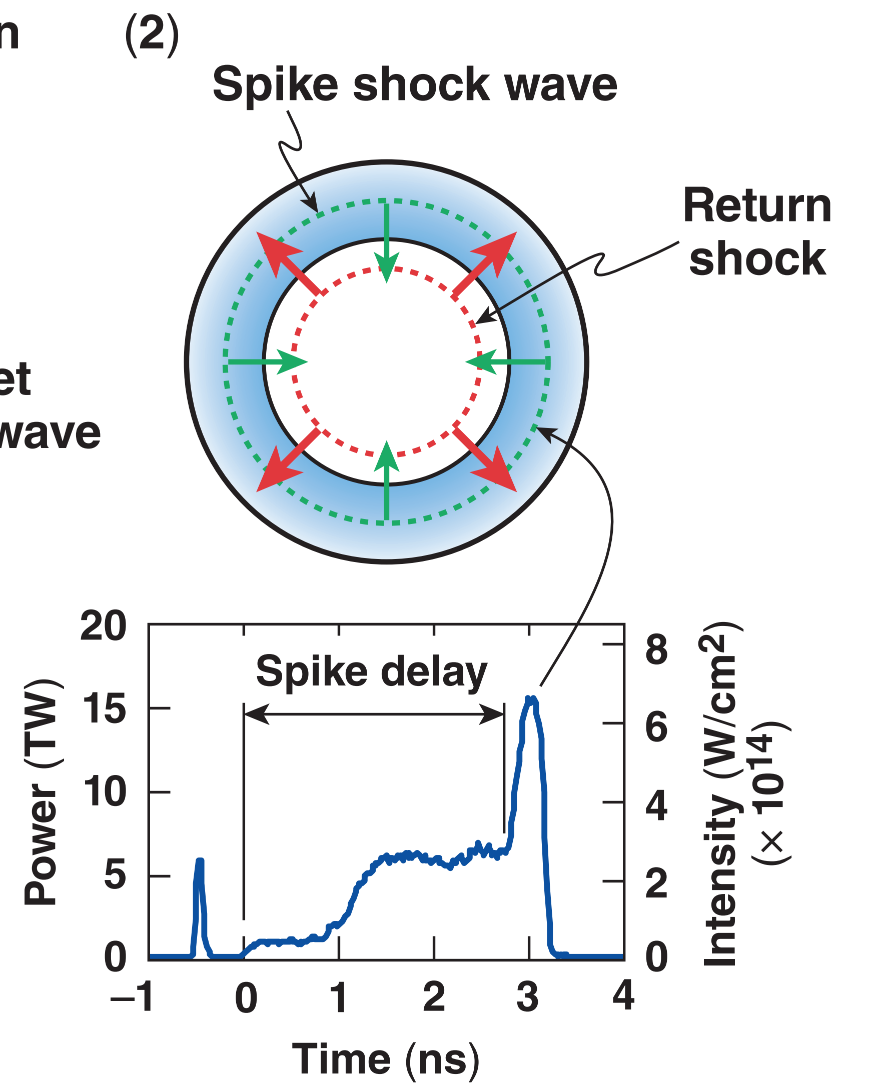
E16129

The correct timing of the shock waves is crucial for an optimized performance of the implosion

FSC

UR LLE

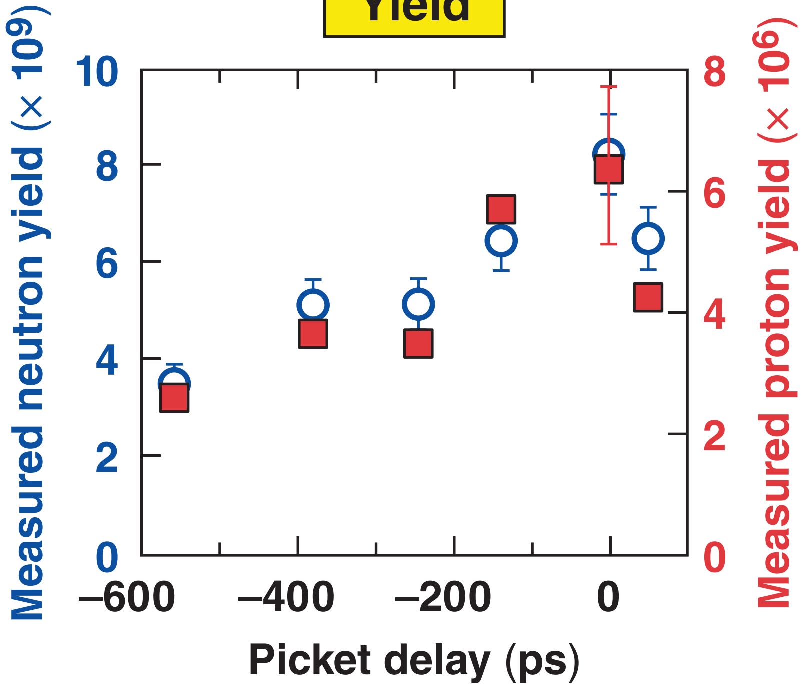




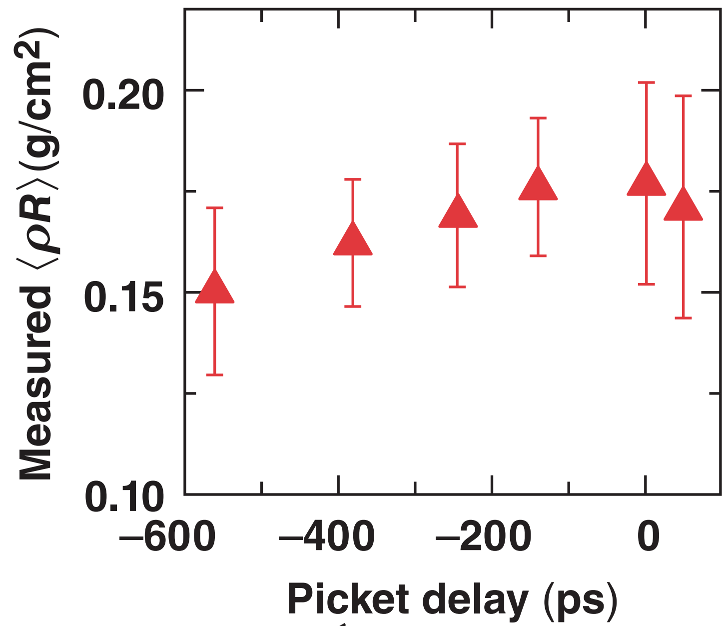
E16130

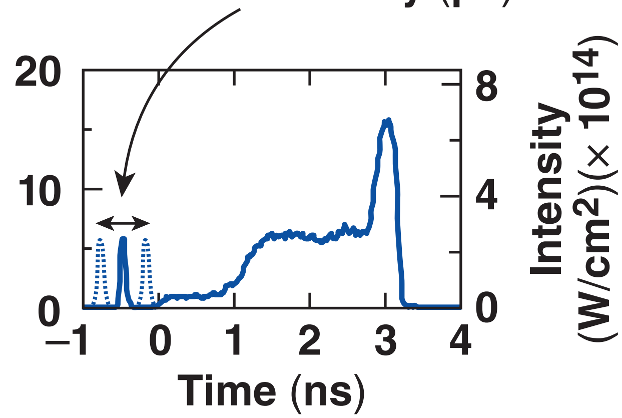
The implosion was optimized with respect to the timing of the picket pulse with fixed spike timing

Yield



Areal density

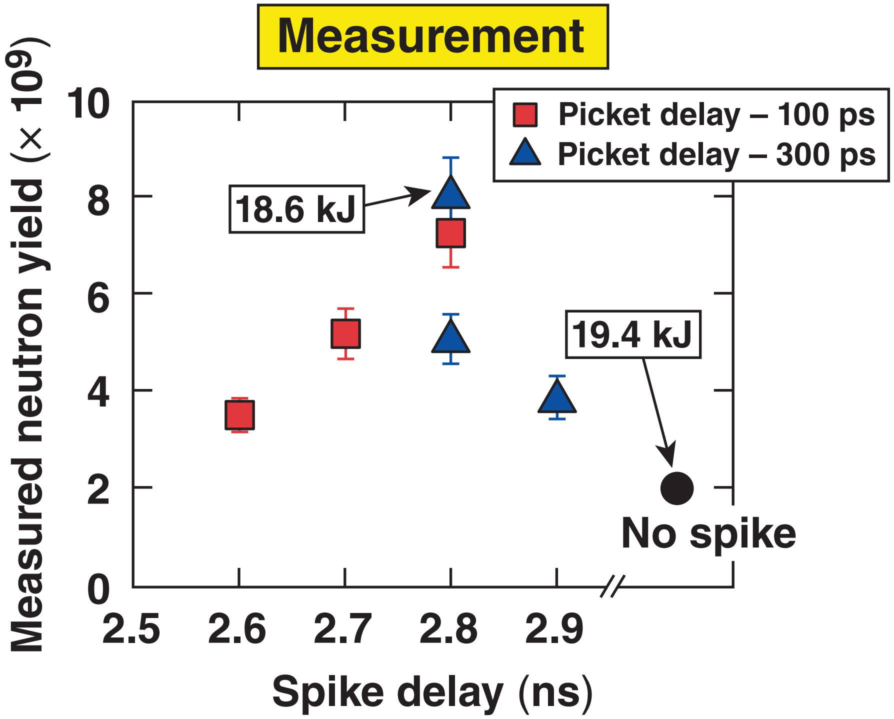


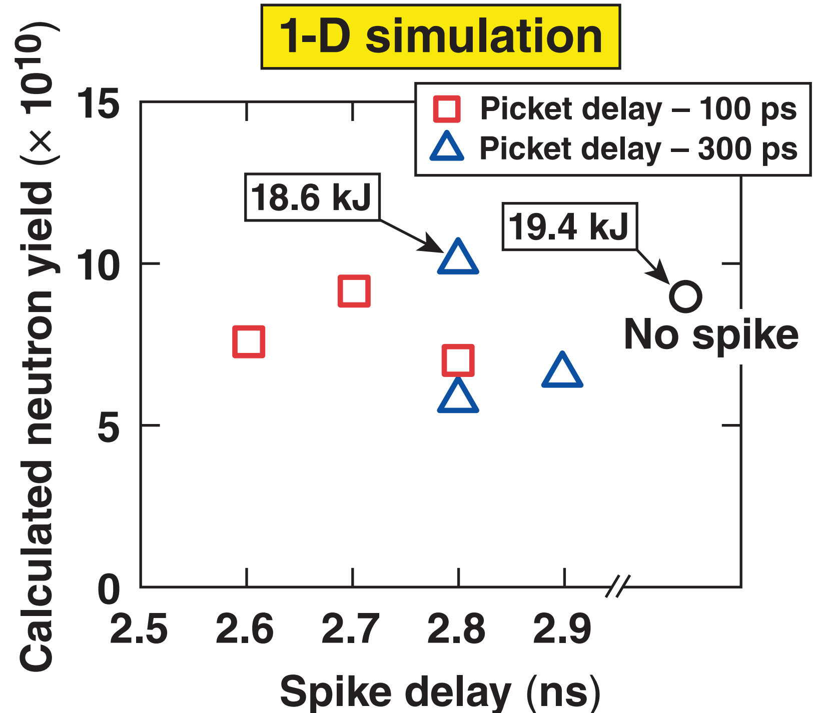


25-atm D_2, E_L ~ 17 kJ,
spike at 2.8 ns

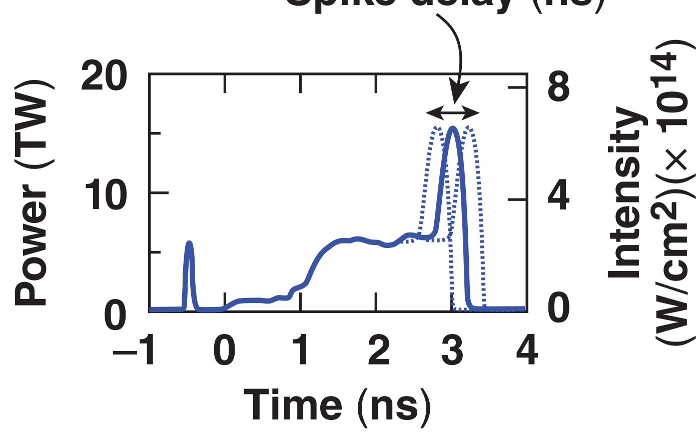
E16131

The spike timing has a significant effect on the measured neutron yield

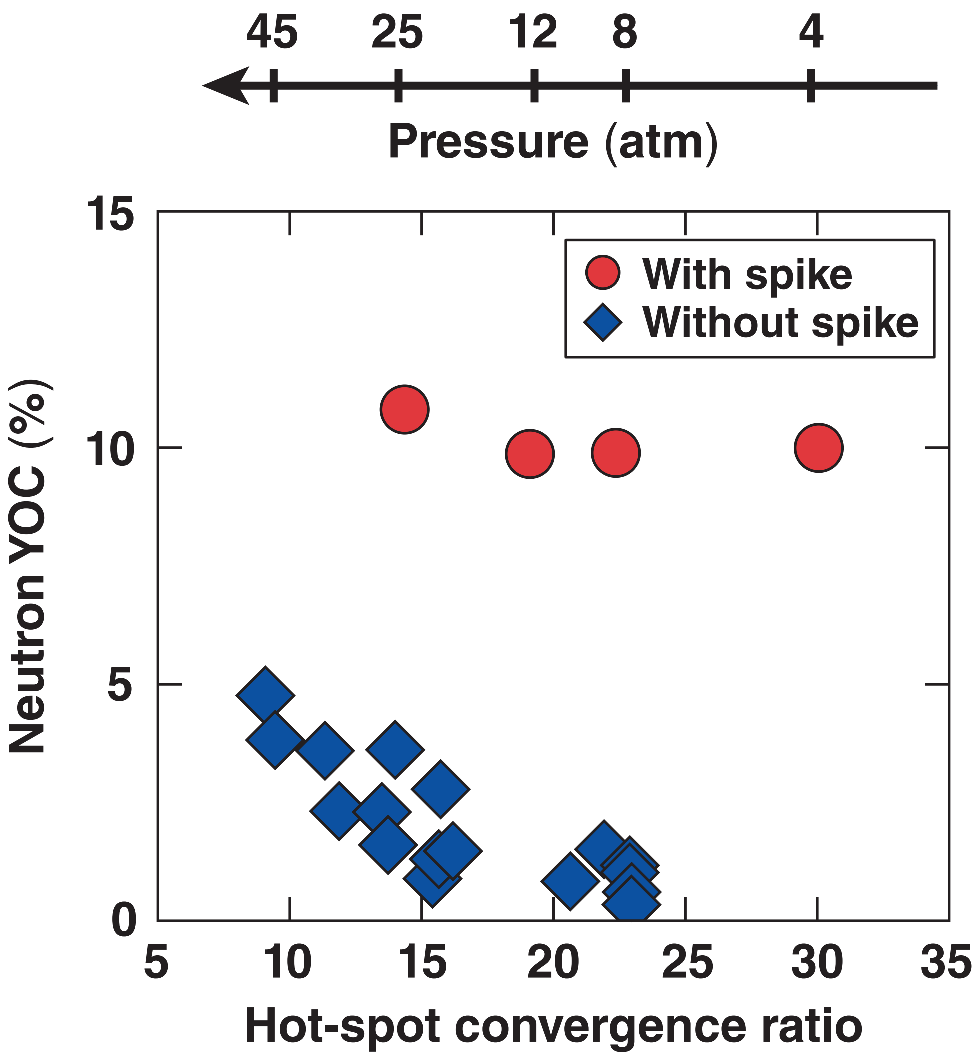




25-atm D_2, E_L = 17 and 19 kJ



The high yield-over-clean at high convergence ratio shows better stability with shock-ignition pulse shape



$$CR = \frac{\text{Inner target radius}}{\text{Minimum hot-spot radius}}$$

The measured to calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.

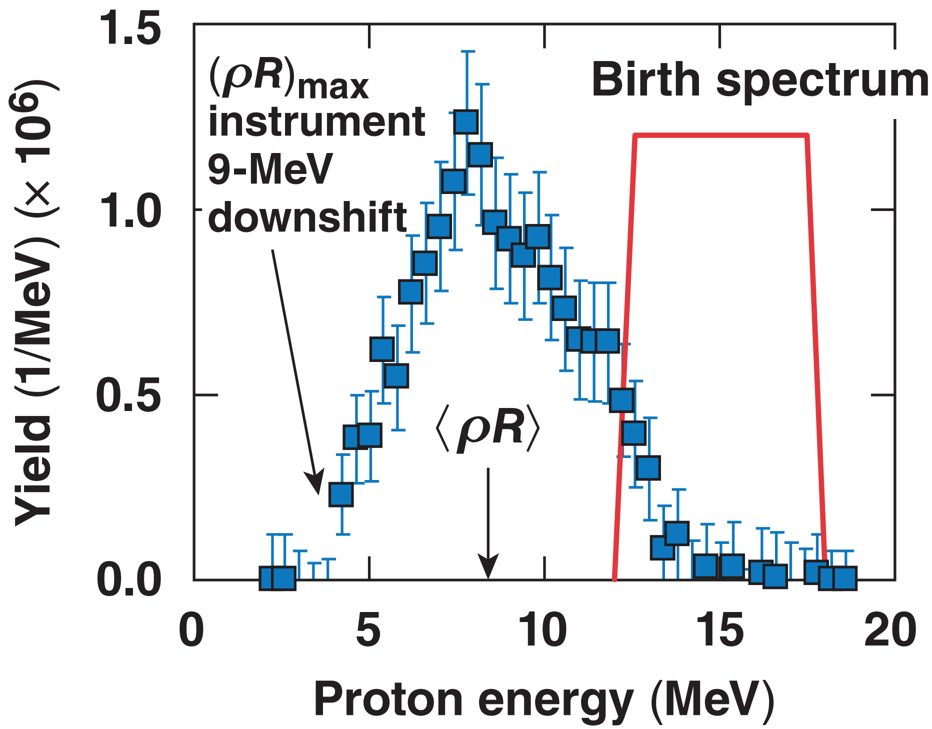
E16133

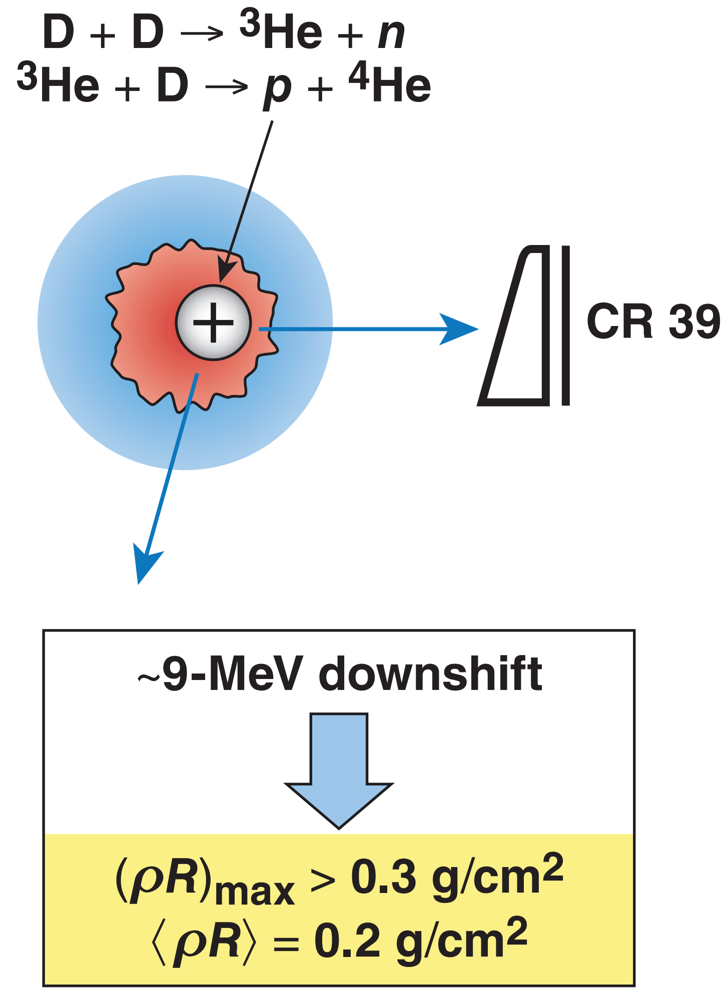
Downshifted secondary proton spectra measure* $\langle \rho R \rangle$ = 0.2 g/cm^2 and $(\rho R)_{max}$ > 0.3 g/cm^2

FSC

UR LLE

Shot 48674, E_L = 18.0 kJ, D_2 8.3 atm

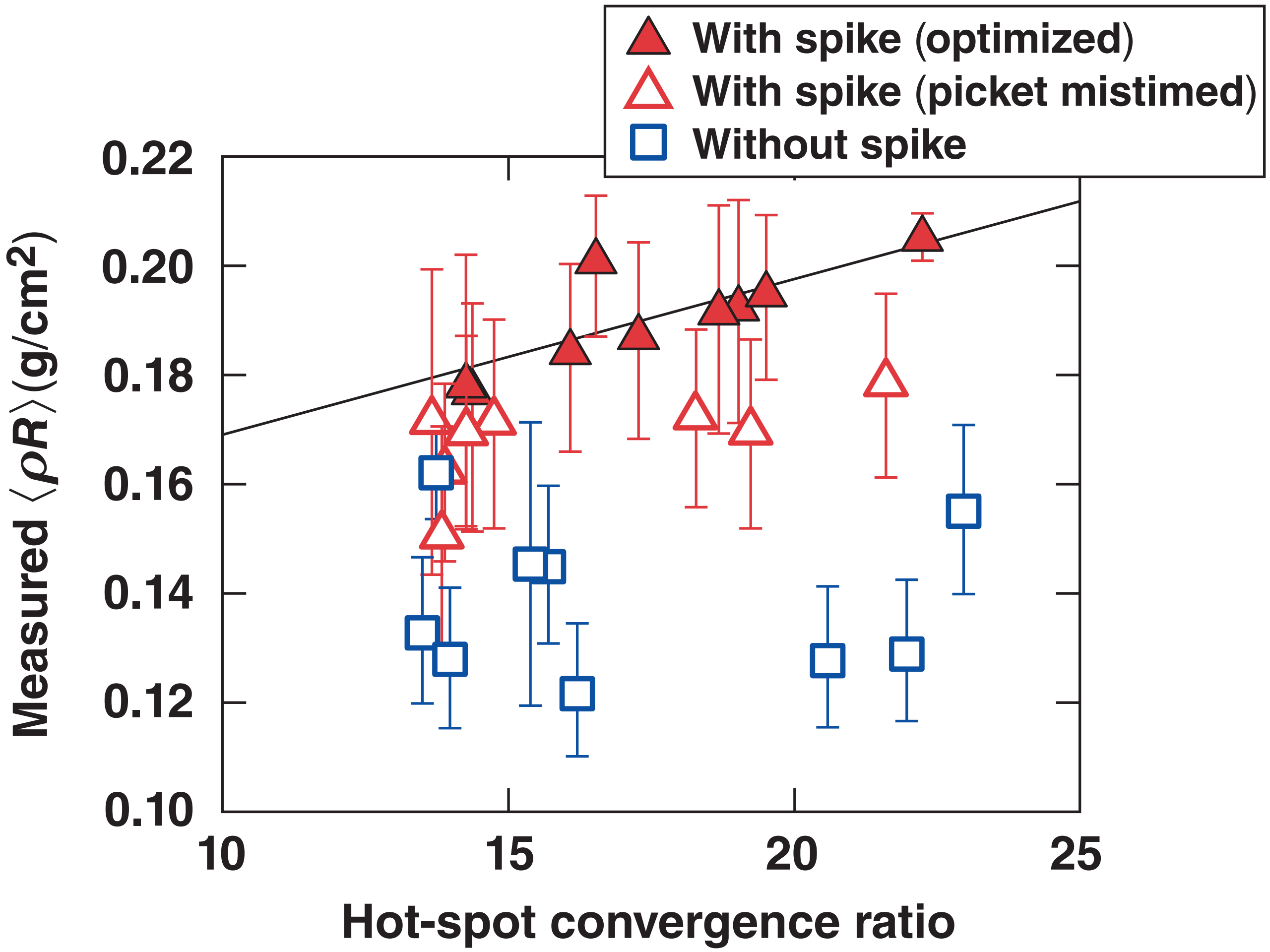




E16134

*F. H. Séguin *et al.*, Rev. Sci. Instrum. 74, 975 (2003).

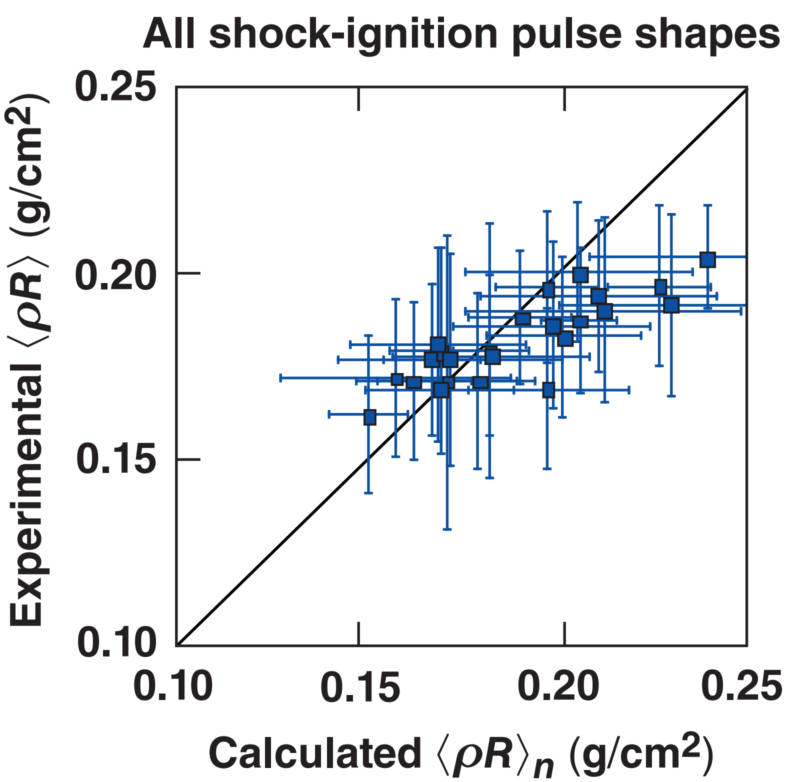
Higher ⟨ρR⟩ exceeding = 0.2 g/cm^2 where measured in implosions with late spike

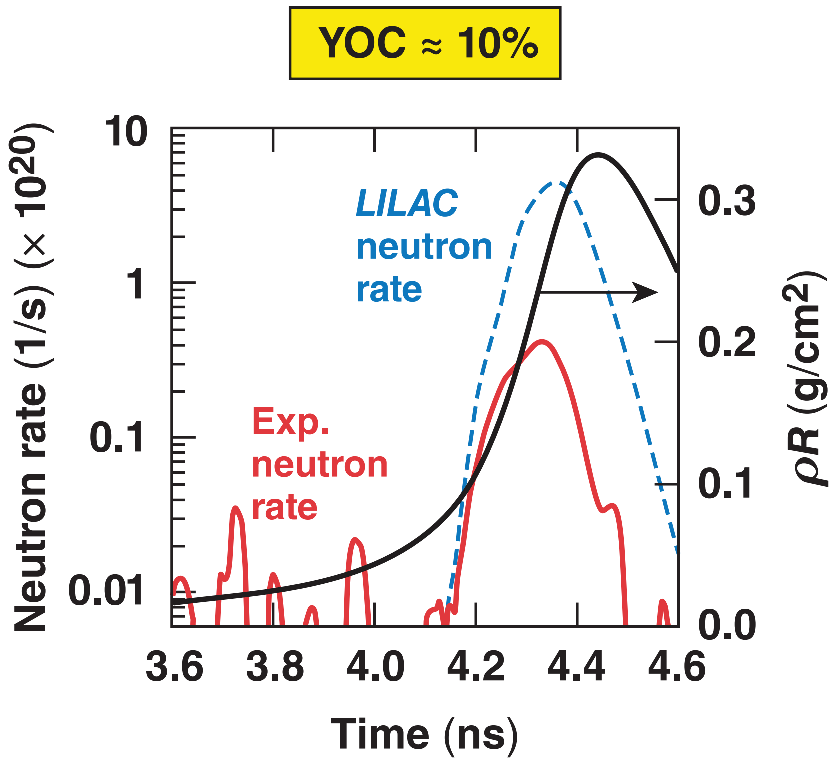


The shock-ignition pulse-shape implosions show an improved performance with respect to compression and neutron yields.

E16136

The fuel assembly is close to the one-dimensional predictions with the code *LILAC*



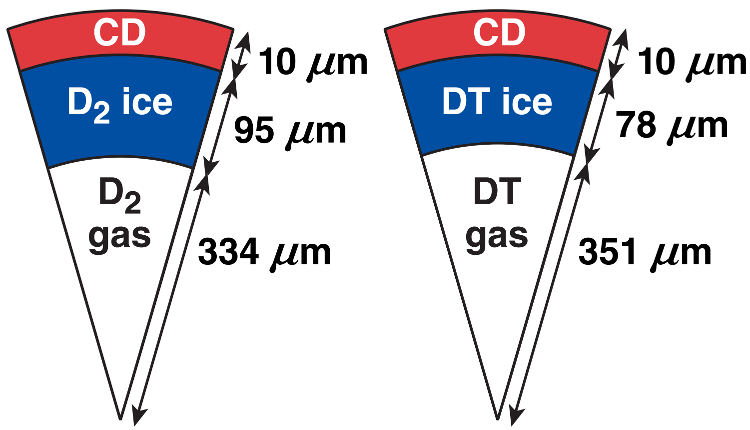


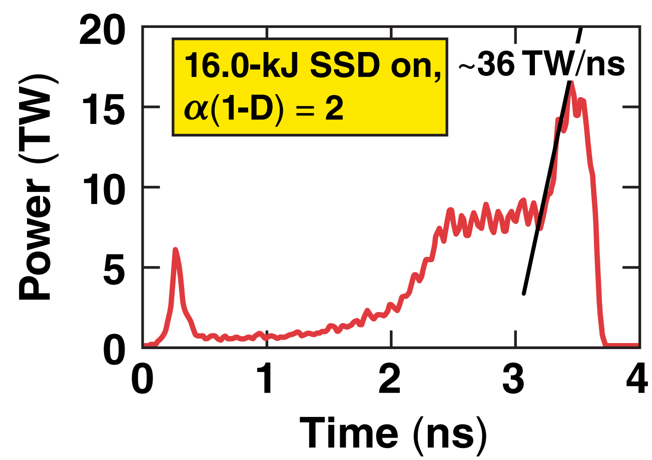
Shot 48674, D_2 8 atm, CR = 22,
E_L = 17.9 kJ, no SSD

E16137

P. B. Radha *et al.*, Bull. Am. Phys. Soc. 51, 106 (2006).

Initial experiments of the shock-ignition concept were performed with cryogenic D_2 and DT targets





- The D_2 implosion measured $\langle \rho R \rangle = 0.18 \pm 0.05$ g/cm^2 achieving 90% of the 1-D prediction (0.20 g/cm^2).
- The neutron YOC's were 5% and 12% for the D_2 and DT implosions.
- The simulations show that no shock was produced by the spike pulse.

> - The first few shock-ignition cryo-implosions on OMEGA were among the best performing (in terms of YOC and ρR) but did not yet exceed the performance of standard pulse shapes.
> - Pulse shape with SSD is not optimal (spike rise time).
> - More cryo shots are coming up in the future.

E16138

Summary/Conclusions

The first experimental results of the shock-ignition concept show significant improvement in performance

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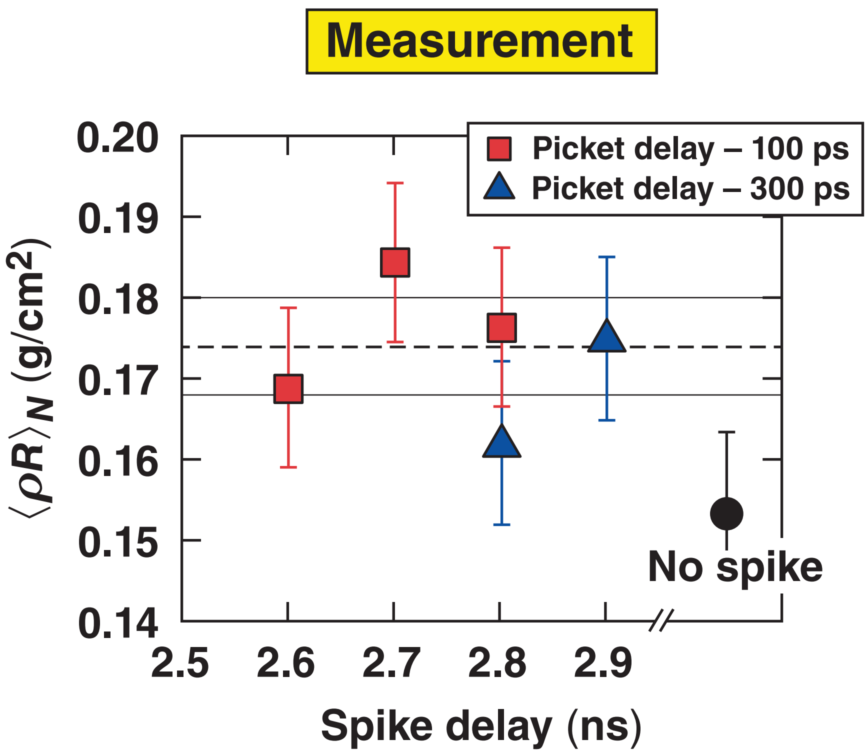
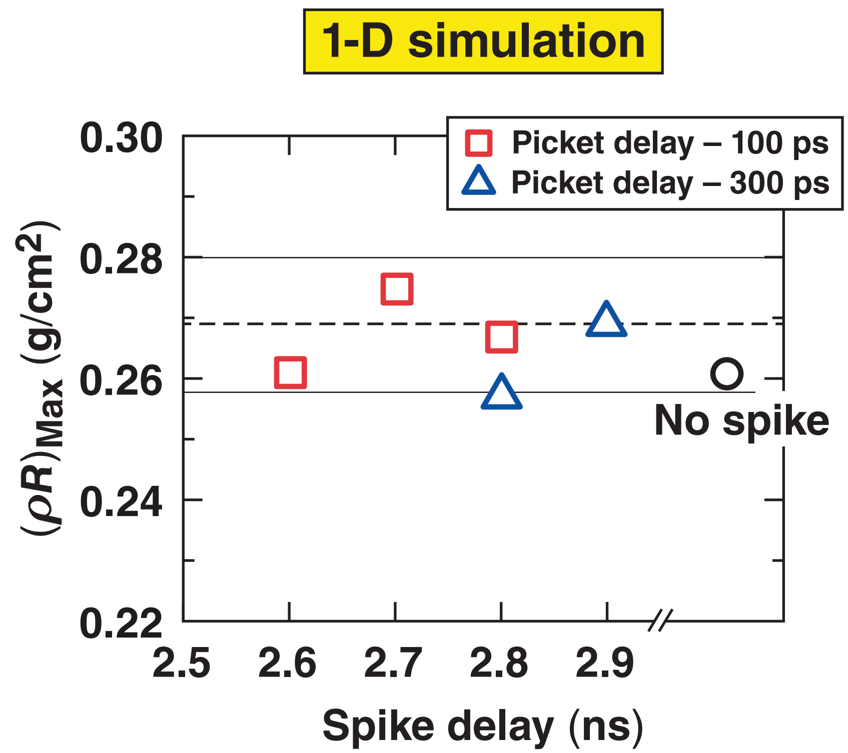
- The spike shock-generated CH-shell implosion showed a factor of ~4 enhanced fusion-product yields and higher $\langle \rho R \rangle$ ~ 0.2 g/cm^2 indicating a higher compression and better stability.

- Initial shock-ignition experiments with cryogenic D_2 and DT targets were performed showing ~1-D–like fuel assembly and up to 12% yield-over-clean.

E16126

The spike pulse provides a higher compression





25-atm D_2, E_L = 17 and 19 kJ

E16135