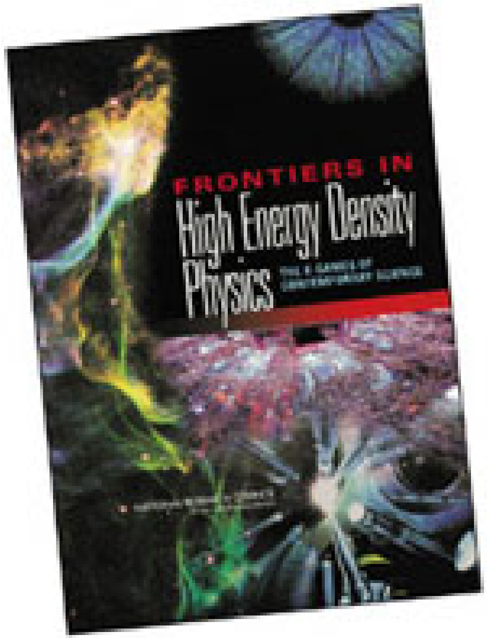
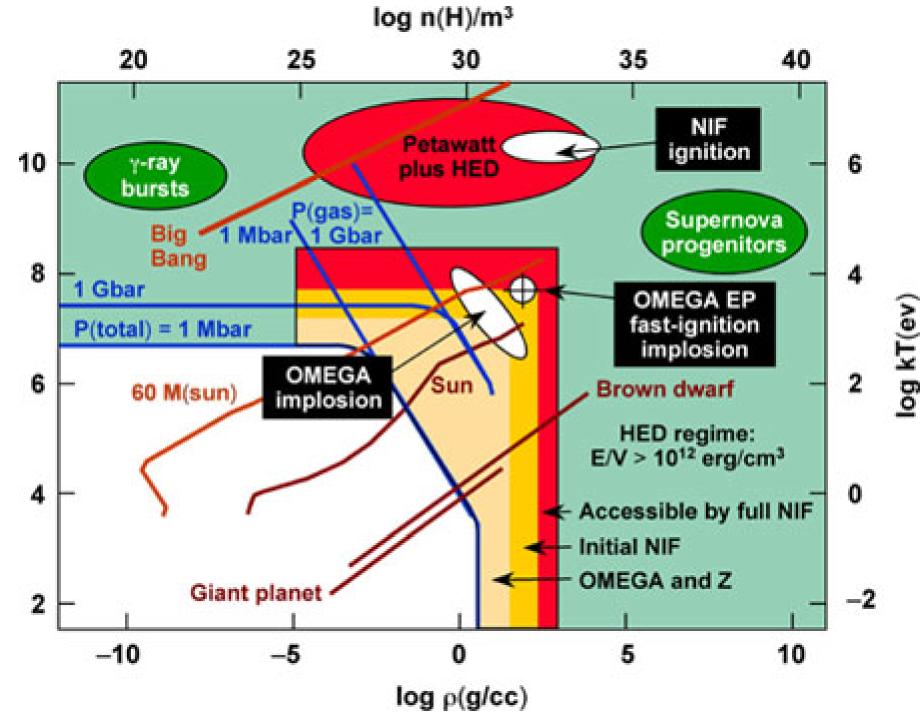
The Davidson's report has defined the field of High Energy Density Physics

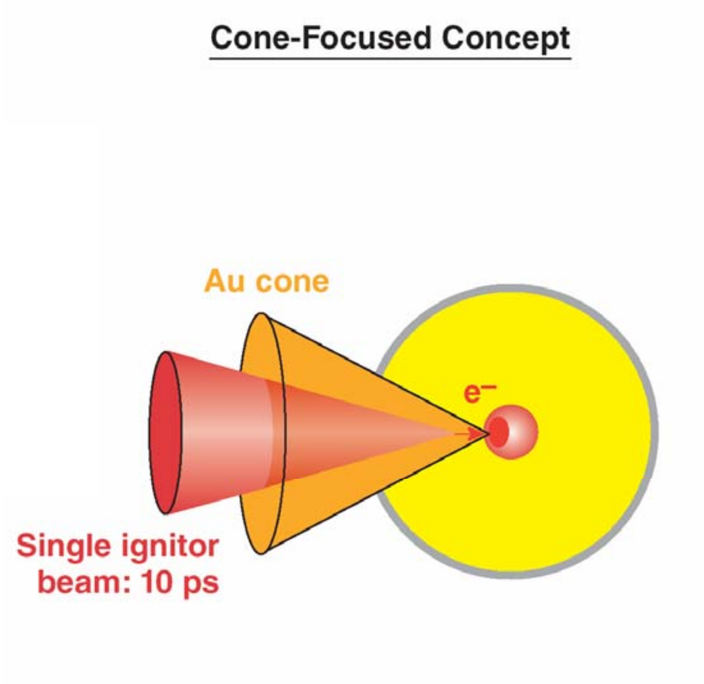


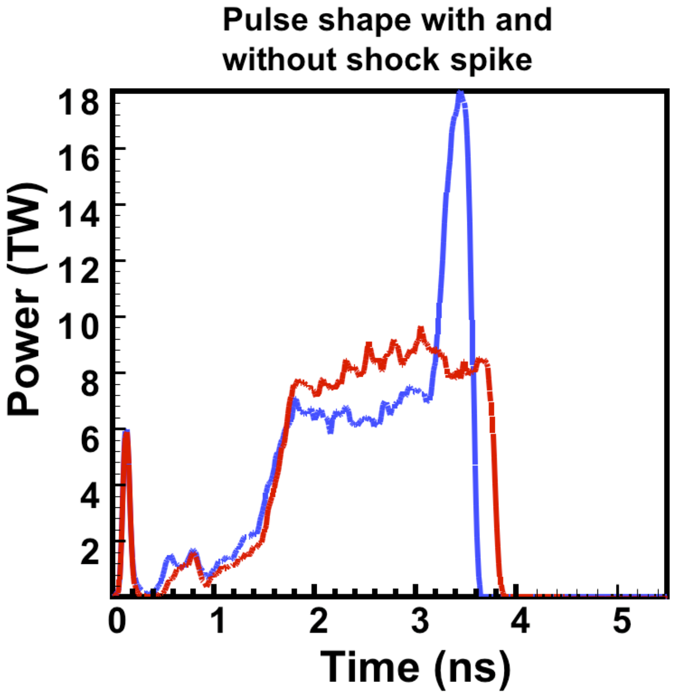


"Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high-energy-density physics. The committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field."

"Frontiers in High Energy Density Physics" (R. Davidson et al.)

2-STEP ICF IGNITION





R. Betti

Fusion Science Center and Laboratory for Laser Energetics

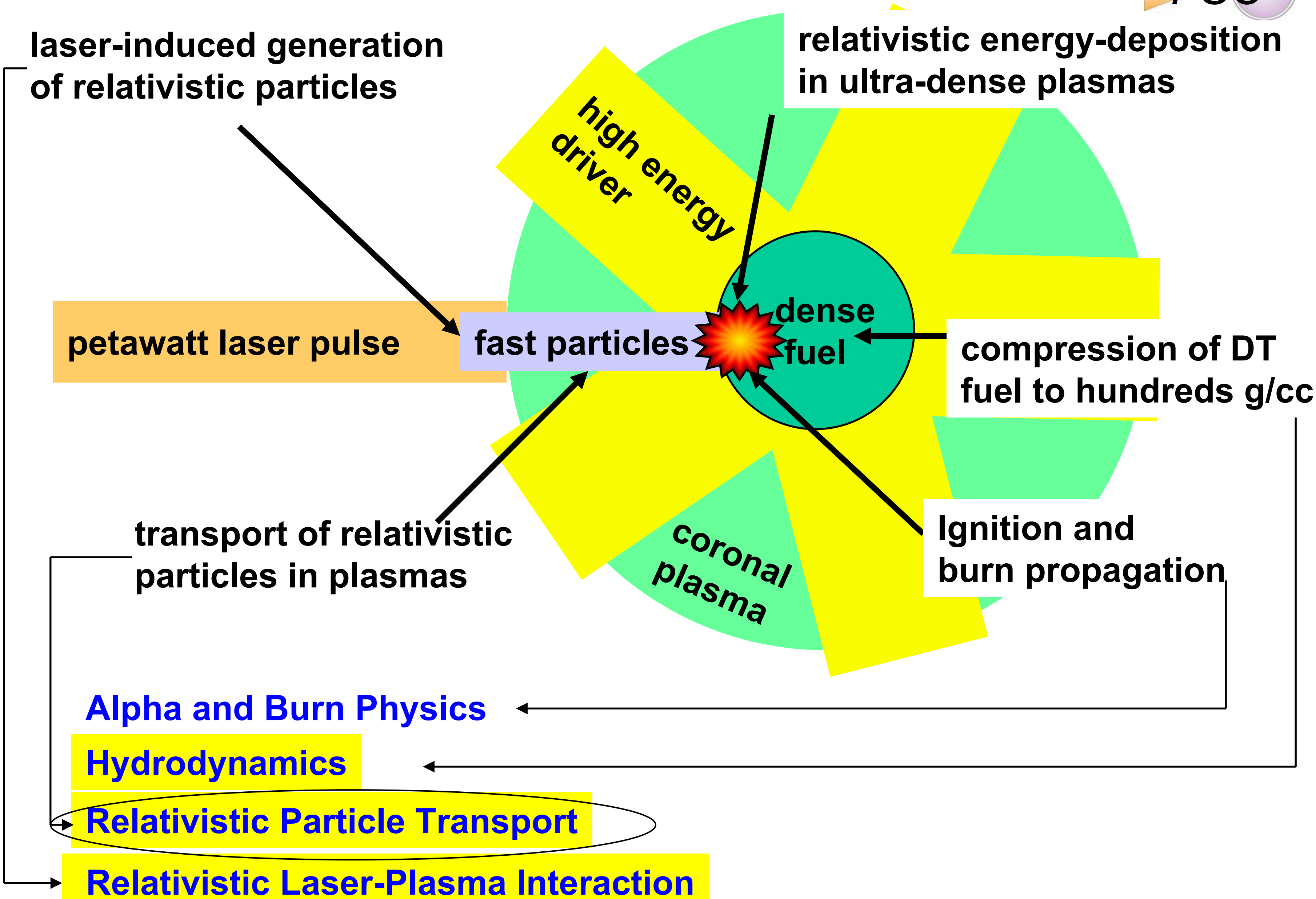
University of Rochester

Symposium on Recent Advances in Plasma Physics

Princeton NJ, June 11-12, 2007

Challenges in FI: hydrodynamics and particle transport

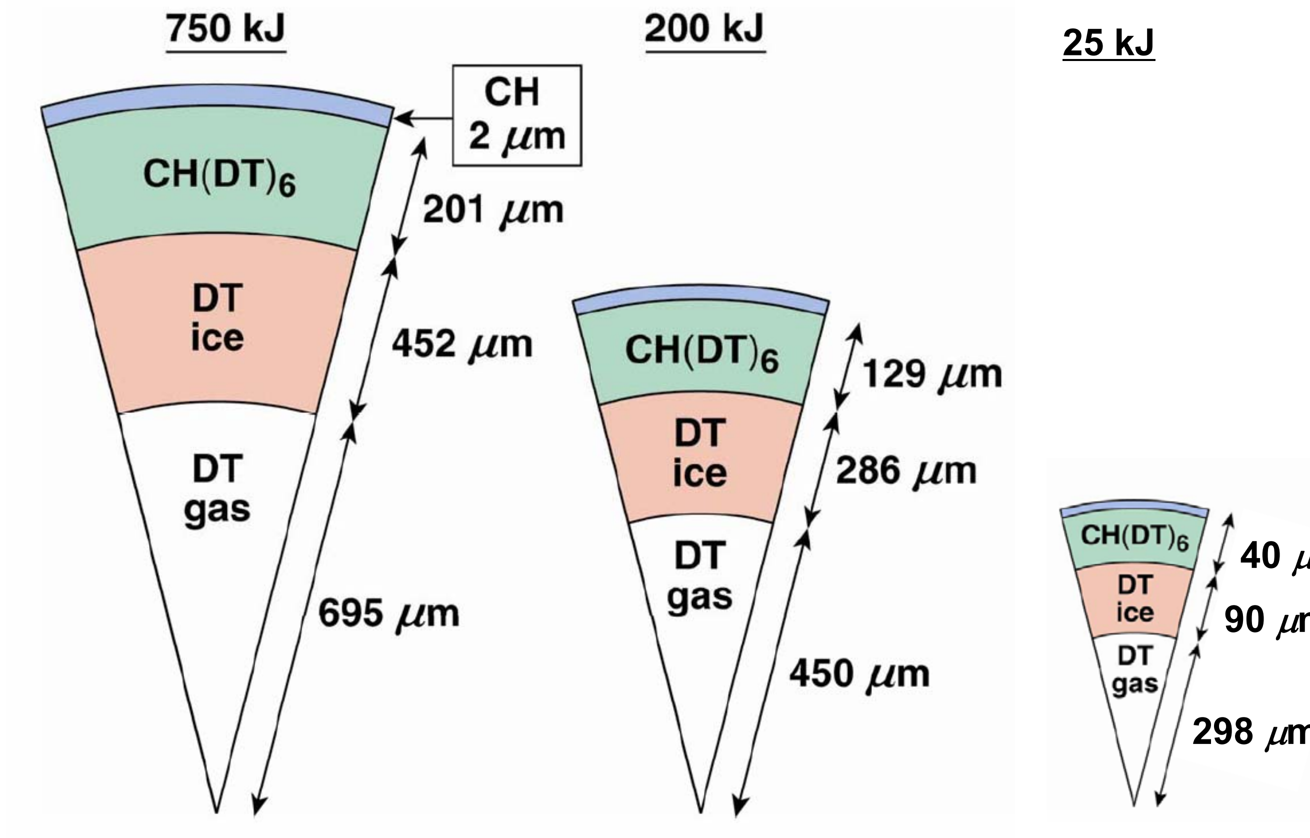
FSC



Target designs for direct-drive fast ignition use massive wetted foam shells insensitive to fluid instability

FSC

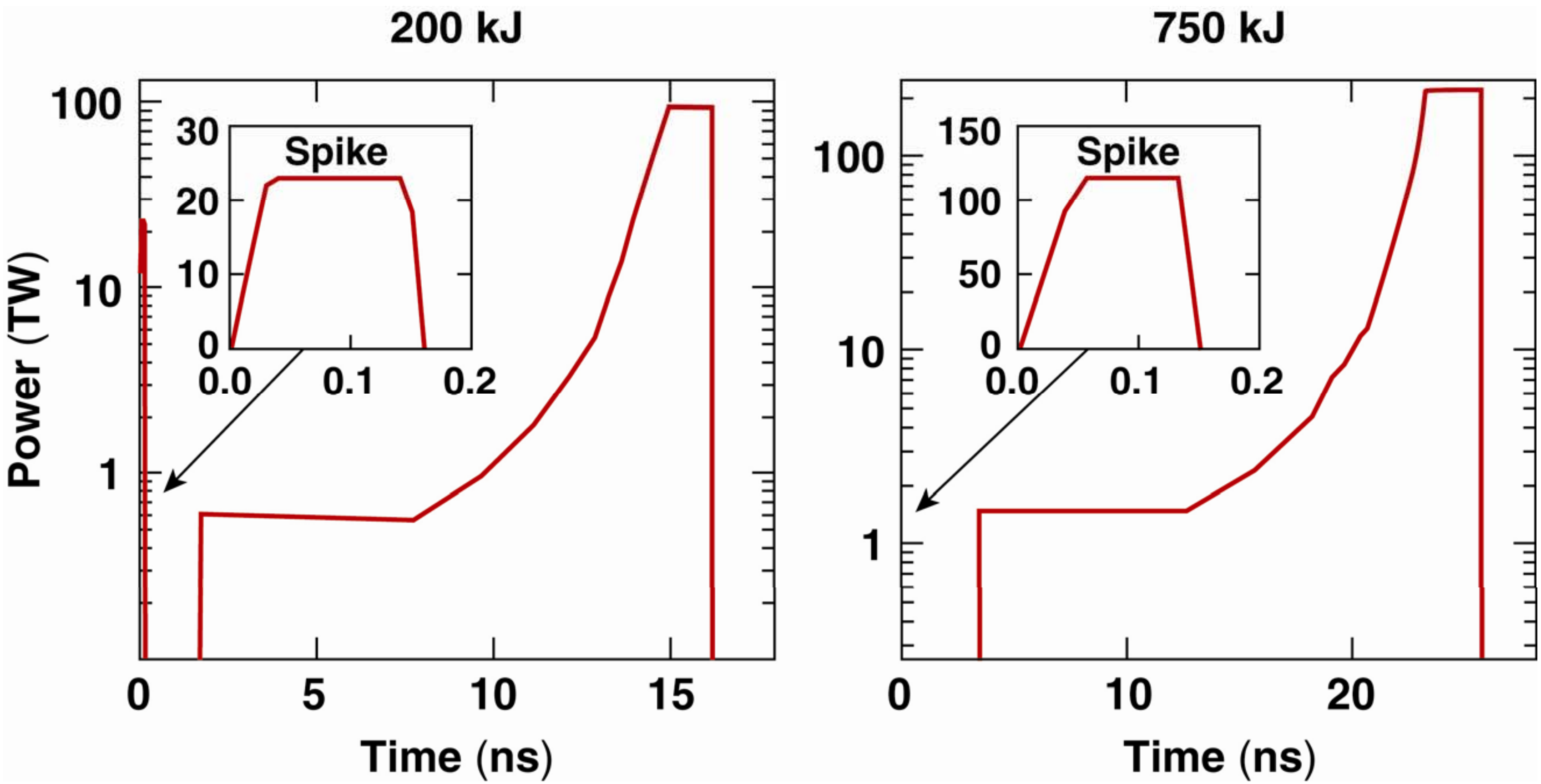
UR LLE



$\rho R \approx 3 g/cm^2$ $\rho R \approx 1.9 g/cm^2$ $\rho R \approx 0.7 g/cm^2$

$\langle \rho \rangle \approx 300\text{-}500 g/cm^3$

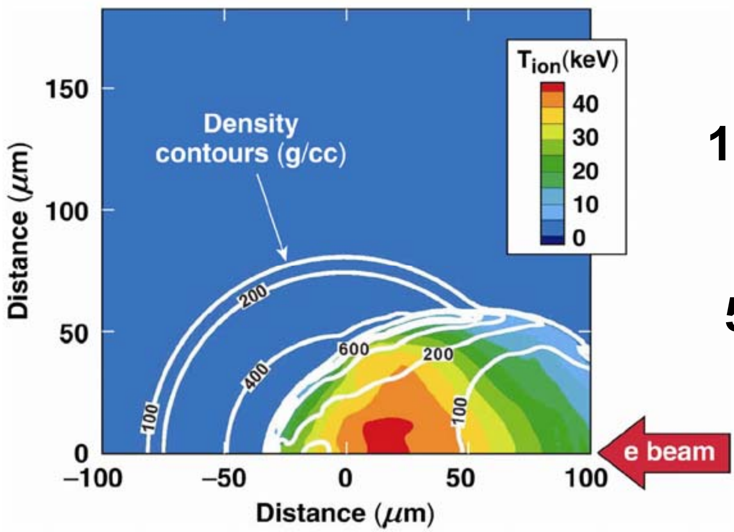
Fast-ignition targets require long laser pulses and high contrast ratios (~100 to 150) within the capabilities of the NIF

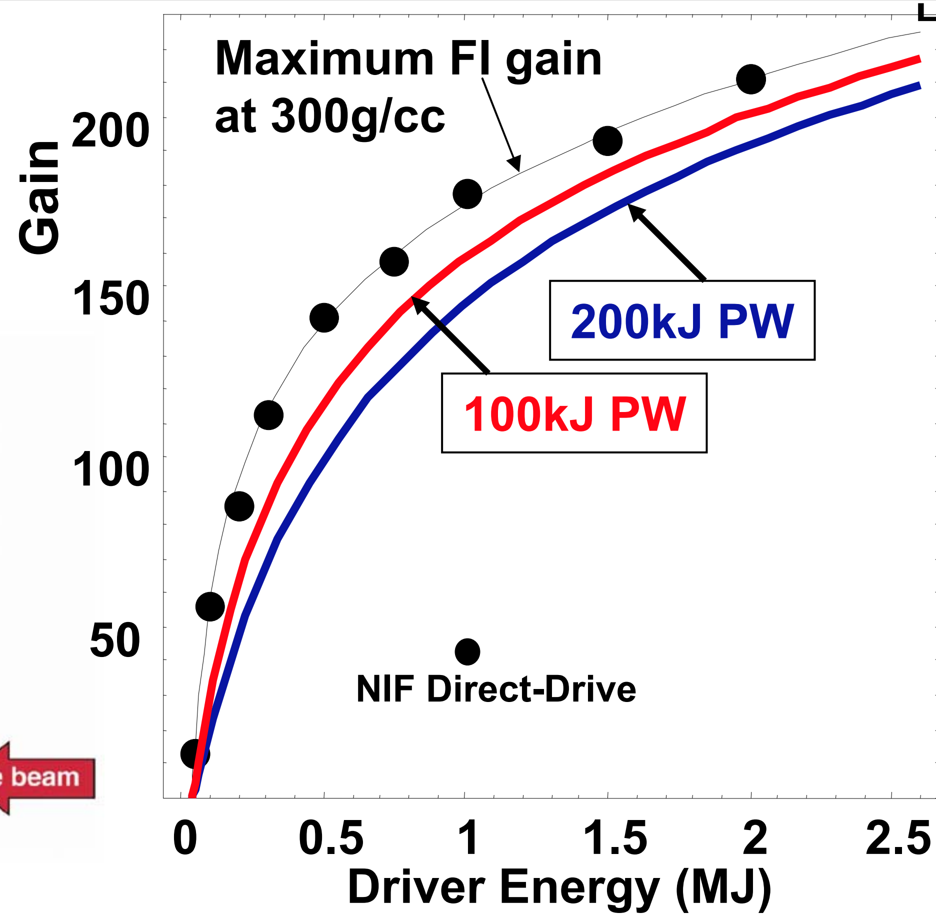


TC7379

2D hydro-simulations of ignition by fast electrons and burn propagation yield fast ignition gain curves

- 2D simulations of ignition and burn by 15kJ, 2MeV, 20μm, 10ps e-beam

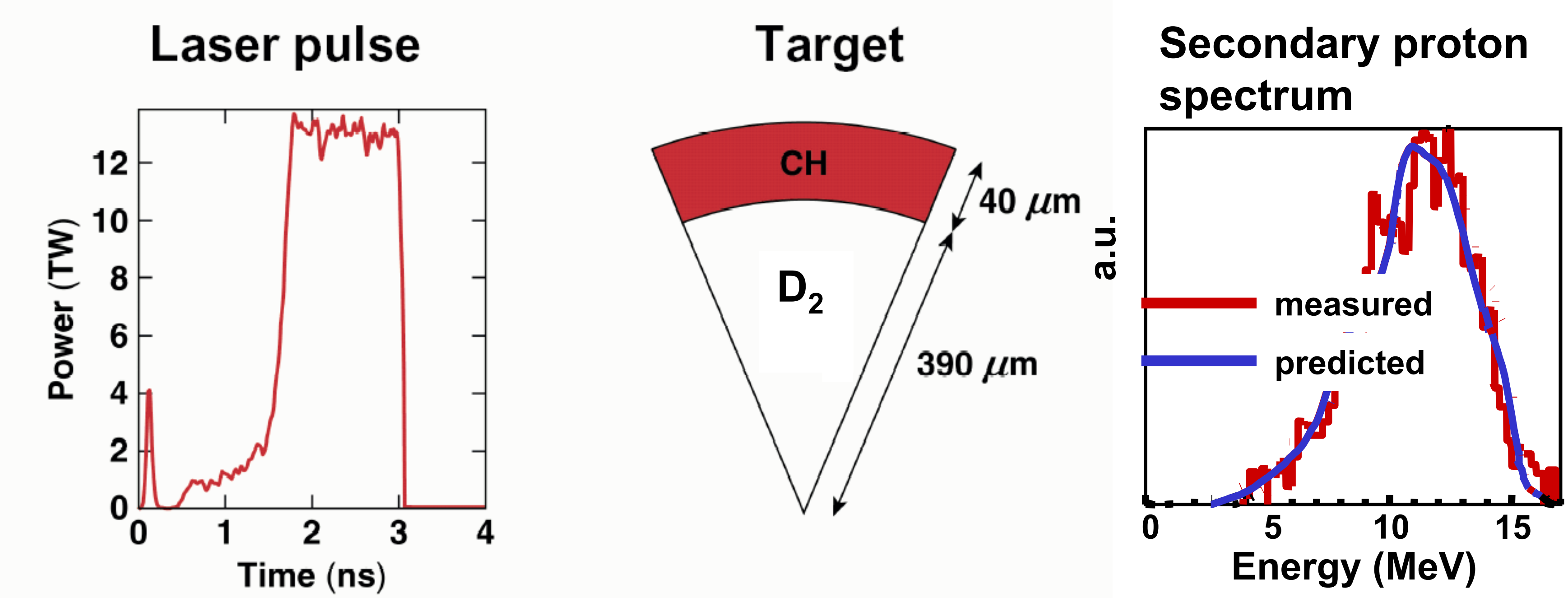




FI allows for significant gains with a few hundred kJ laser driver

Slow implosions with low adiabat were tested on OMEGA D-^{3}He fusion proton energy loss measured the high ρR

$E_L \approx 20kJ$ $P \approx 25atm$ $\alpha \approx 1.3$ $V \approx 2 \bullet 10^7 cm/s$



- Peak ρR is 0.26g/cm^2, the highest ρR to date on OMEGA
- Empty shells would achieve ρR≈0.7g/cm^2 and stop 4MeV electrons

C. Zhou, W. Theobald, R. Betti, P.B. Radha, V. Smalyuk, *et al*, Phys. Rev. Lett. 98: 025004 (2007)

According to the ponderomotive scaling, ignition laser pulses can produce electrons with E>>1MeV that are not stopped in the dense core

FSC

UR LLE

Ponderomotive temperature scaling:[1]

$$\langle E_{hot} \rangle = \left(\frac{I(\lambda / 1.054 \mu m)^2}{10^{19}\ \mathrm{W\ cm^{-2}}} \right)^{1/2} \mathrm{MeV}$$

Electron range:

$$R = 0.6 \times \langle E_{hot} \rangle \ \mathrm{g/cm^2}$$

E_{hot}>>1→ Electron range greatly exceeds the optimal range for fast ignition

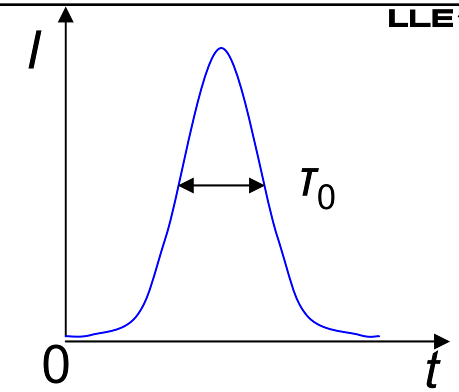
[1] S.C. Wilks et al., Phys. Rev. Lett. 69, 1383 (1992)
[2] S. Atzeni, Phys. Plasmas 6, 3316 (1999)

The minimum PW laser energy for ignition exceeds 100 kJ for λ_L=1.05 μm and ponderomotive scaling for E_{hot}

FSC UR LLE

Simulations:

- **Gaussian laser pulses**
- **Maxwellian electrons**



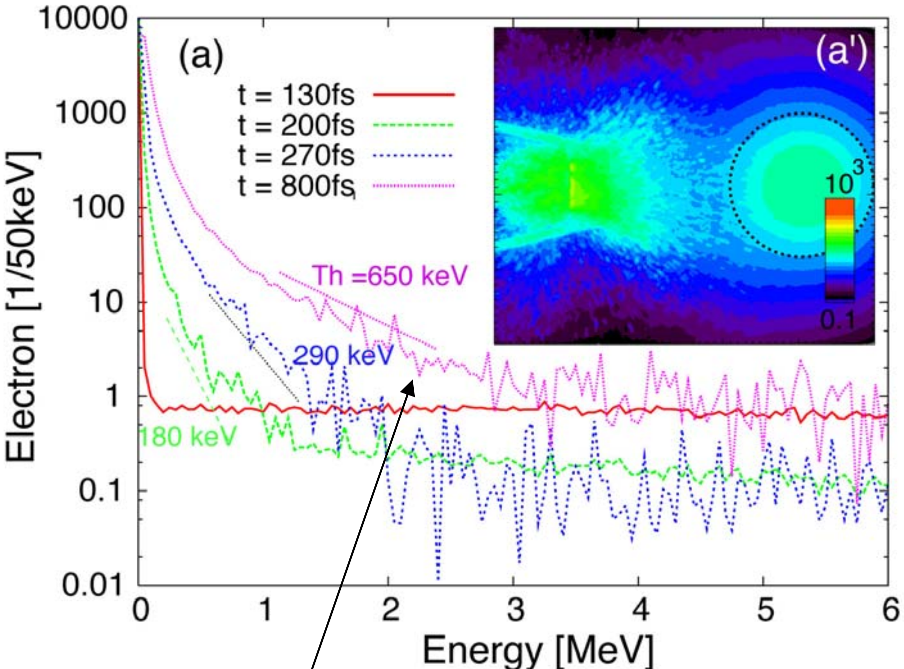
300 kJ target $\lambda = 1.054\ \mu m:$

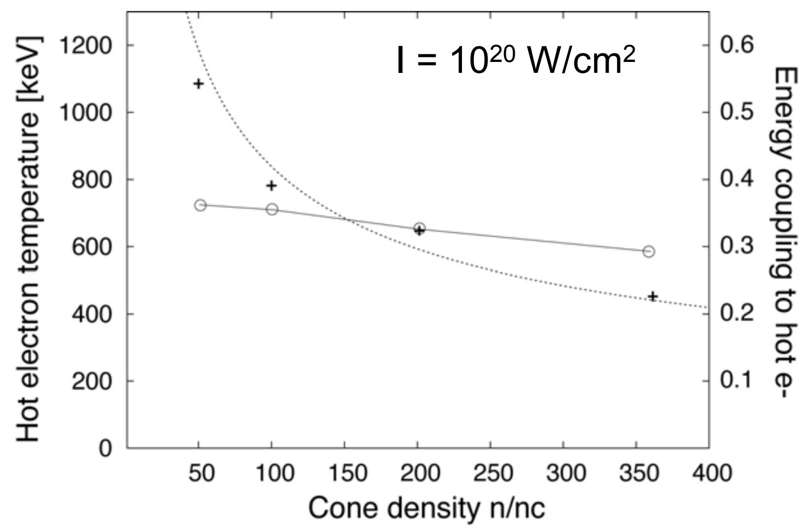
η_{PW}	r_0 (μm)	τ_0 (ps)	Min. PW laser energy (kJ)	Electron beam energy (kJ)	$\langle E_{hot} \rangle$ (MeV)	E-beam – fuel coupl. eff.
0.3	26	16	235	71	7.6	0.69
0.5	23	14	105	53	6	0.76

A. Solodov, et al, Phys. Plasmas in Press

PICLS simulations show that the hot-electron energy is less than predicted by the ponderomotive scaling

FSC





The energy of the hot-electrons reaching the core is ≤ 1MeV

Higher cone densities lead to less energetic electrons

Y. Sentoku, et al, submitted to Phys. Rev. Lett

SHOCK IGNITION

As a tool to improve the ignition conditions of conventional ICF

Shock Ignition

SI

Requires a relatively weak shock

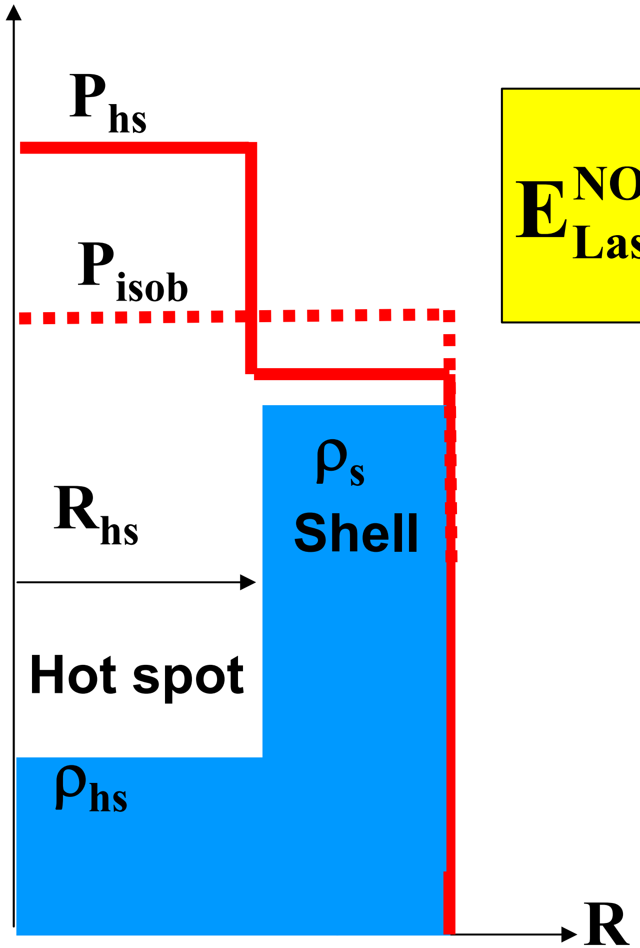
As a true two-step ignition process.

Shock FAST ignition

SFI

Requires a strong shock

SI. The ignition energy is lower in a non-isobaric fuel assembly with a peaked pressure profile



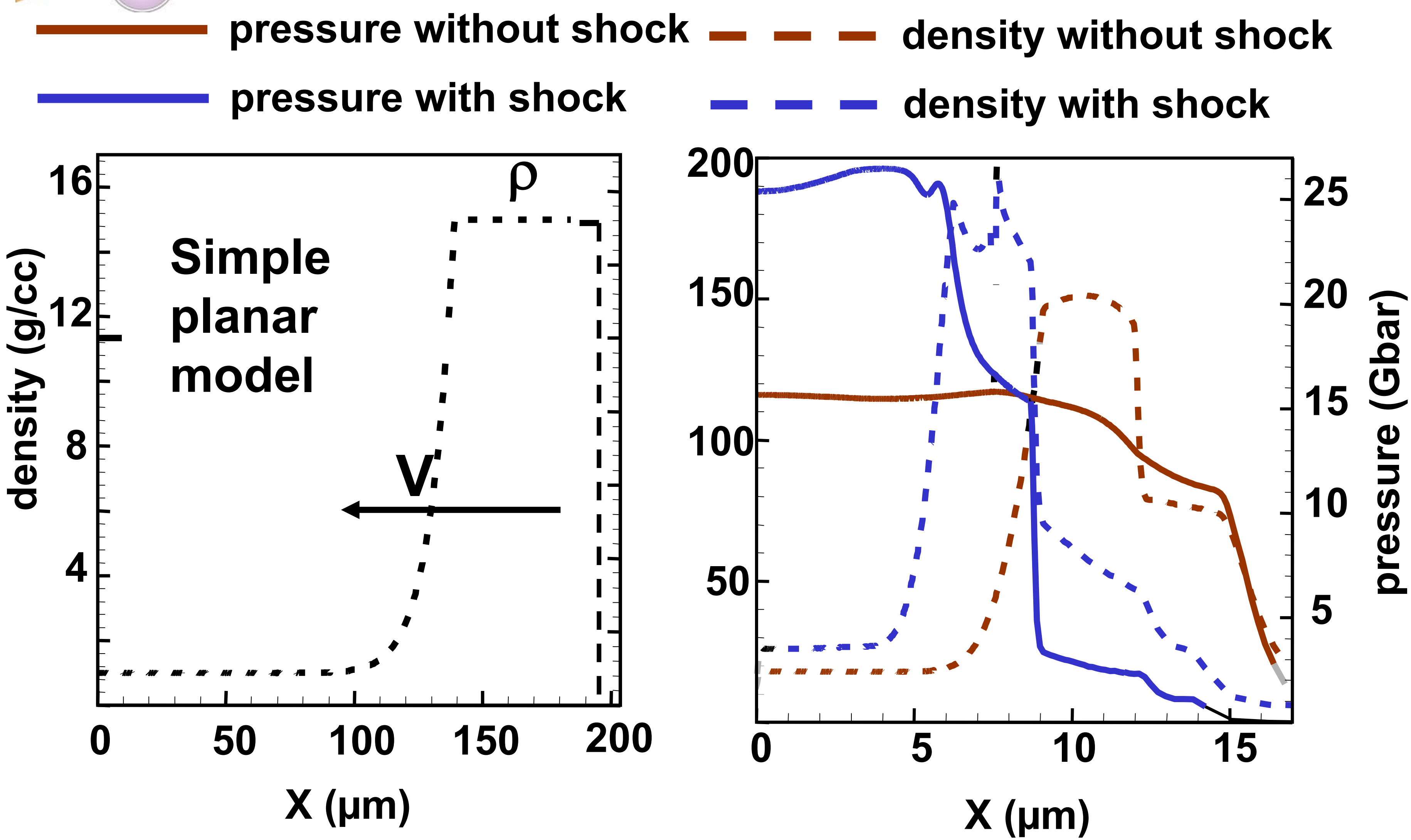
$$E_{Laser}^{NON\text{-}isob.\text{-}ign.} \sim \frac{E_{Laser}^{isob.\text{-}ign.}}{\Phi} + \Delta E^{non\text{-}isob}$$

For adiabatic compression of the hot spot

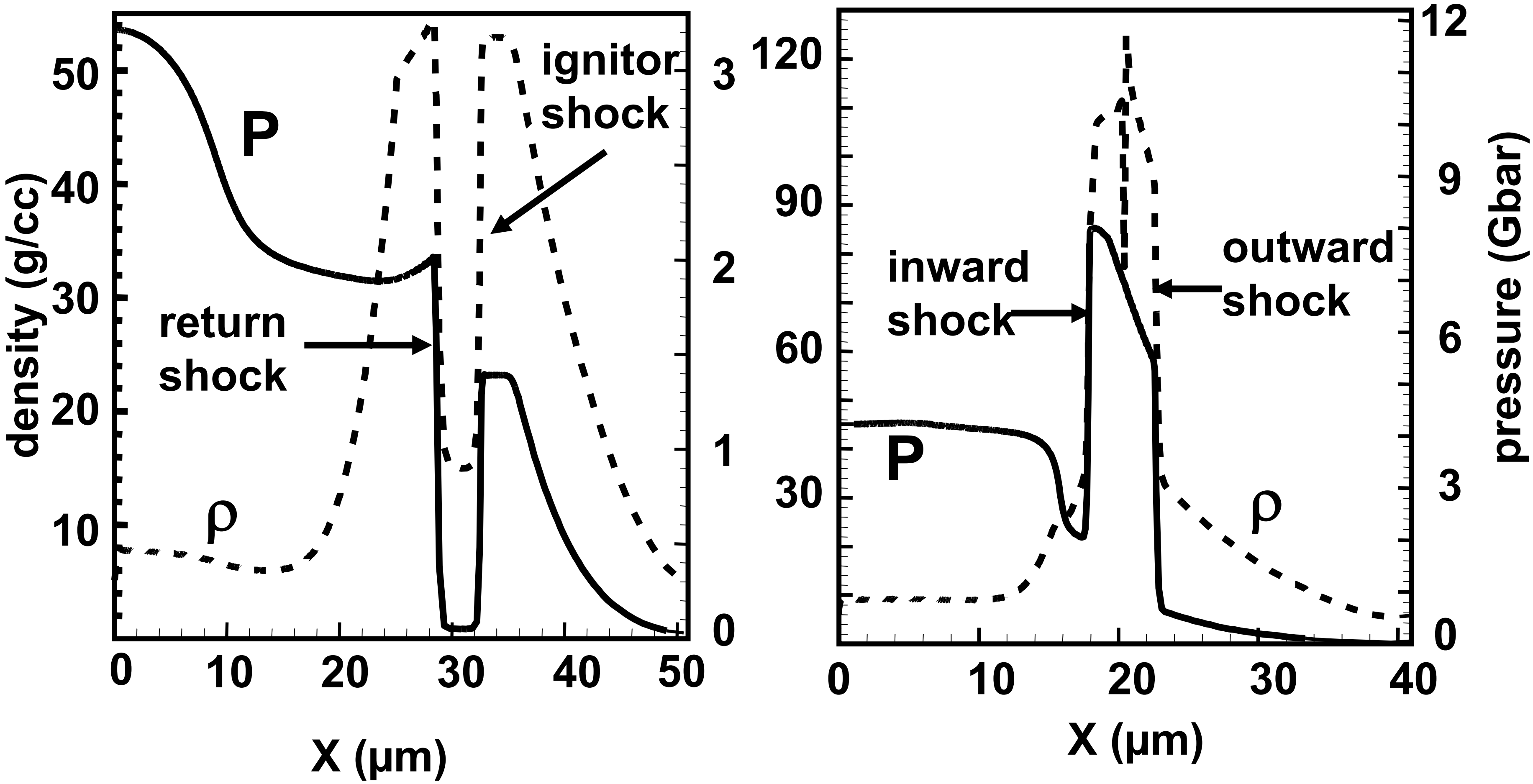
$$\Phi \approx \left(\frac{P_{hs}}{P_{iso}} \right)^3$$

R. Betti, K. Anderson,C. Zhou, J. Perkins, W. Theobald, A. Solodov, Phys. Rev. Lett. 98: 155001 (2007)

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

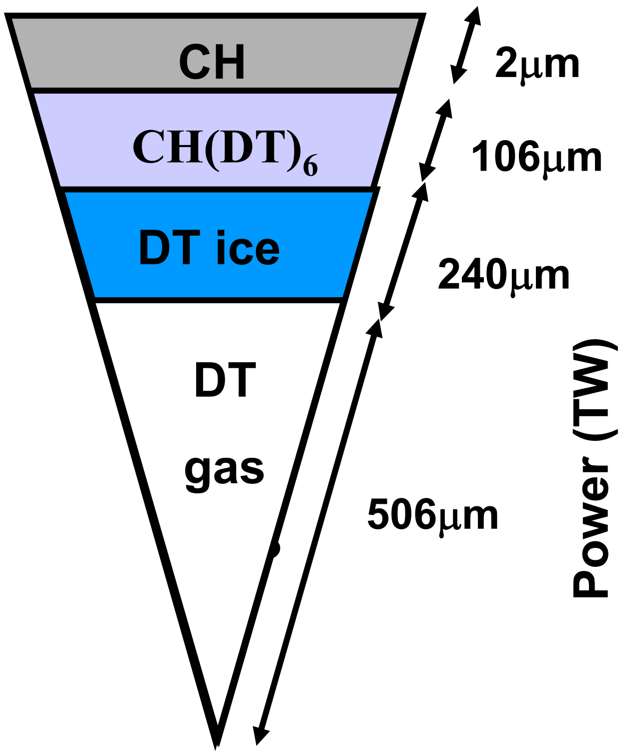


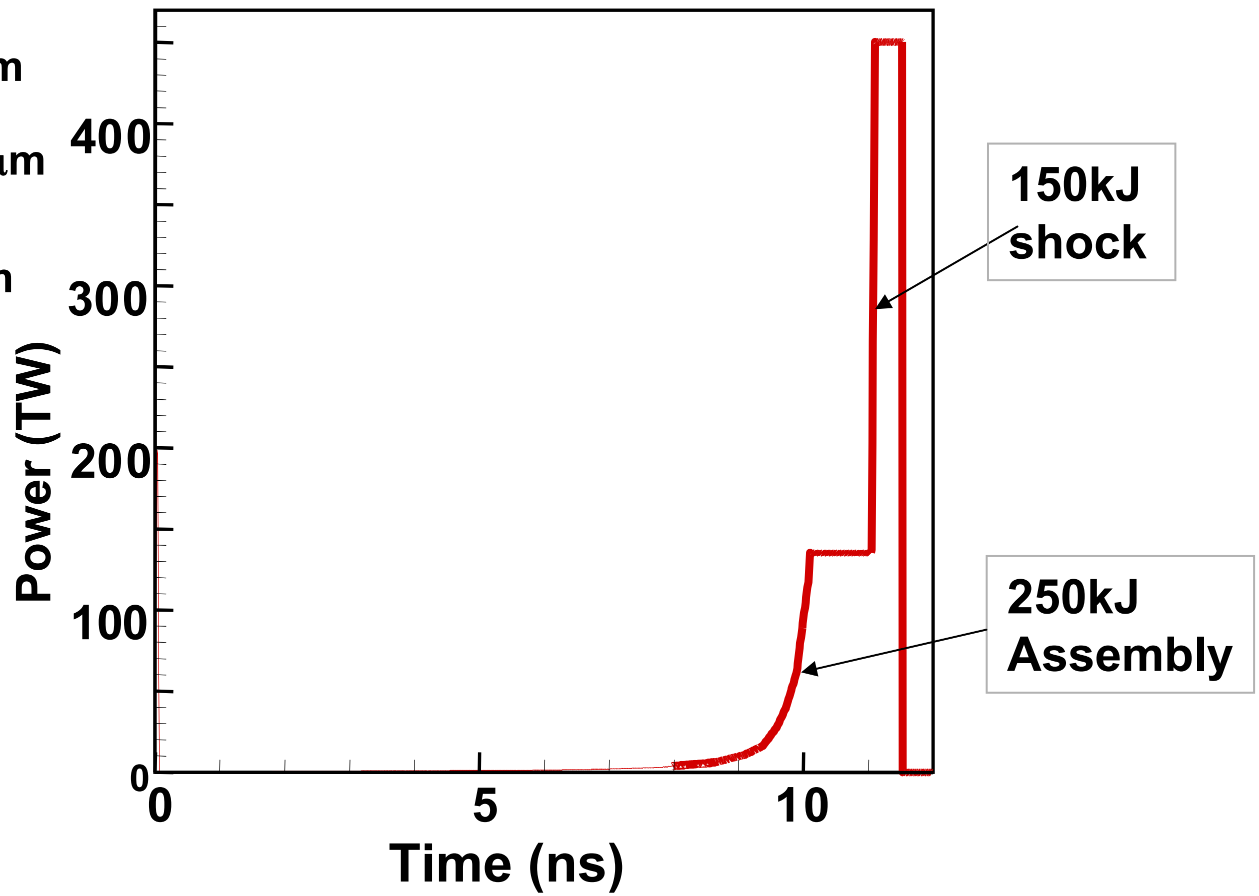
SI. Producing a non-isobaric assembly requires the collision of the ignitor shock with the return shock. The two colliding shocks have similar pressures.



SI. The ignitor shock can be launched with a spike of the laser intensity

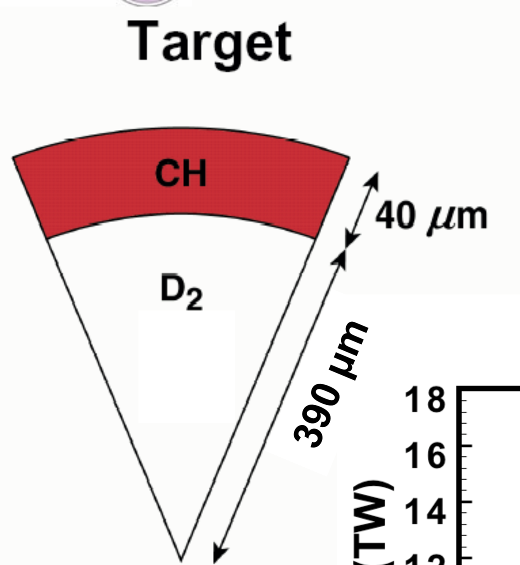
E_L=400kJ, V_i=2.4e7cm/s, α=0.7-1, λ_L=0.35μm





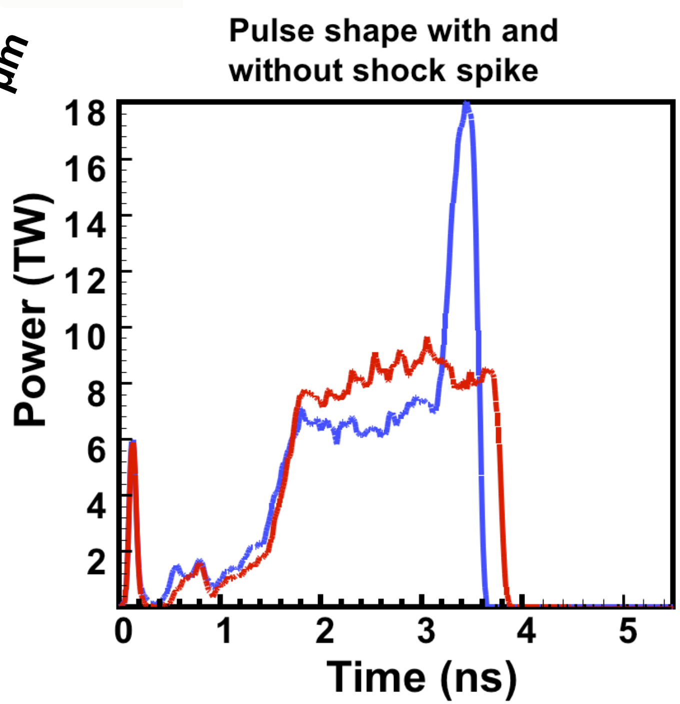
Minimum shock energy for ignition = 50kJ, total energy = 300kJ

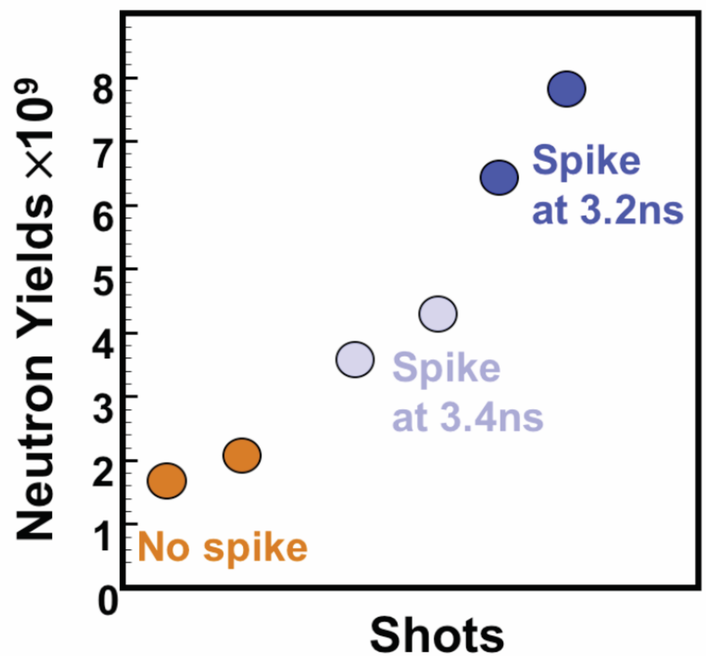
SI. The shock ignition concept has been tested on OMEGA



W. Theobald,,
C. Zhou,
et al
(UR-LLE)

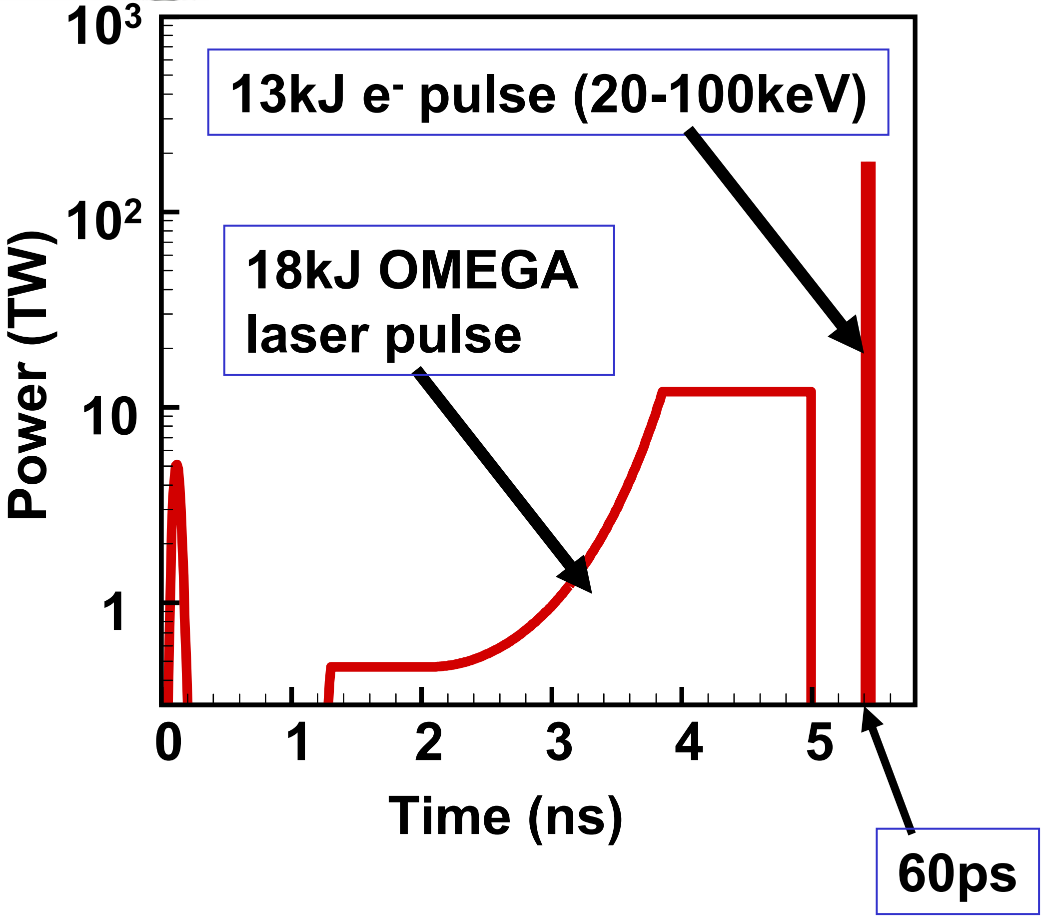
E_L=17kJ
α≈1.3

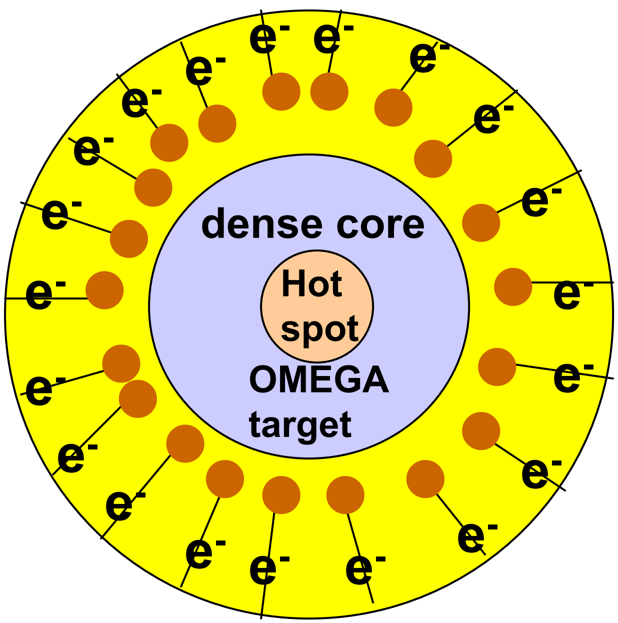




The neutron yield increases considerably when a shock is launched at the end of the pulse

SFI. A true 2-step shock-ignition scheme requires much greater energy in the shock. Conventional laser-driven thermal waves are too inefficient.

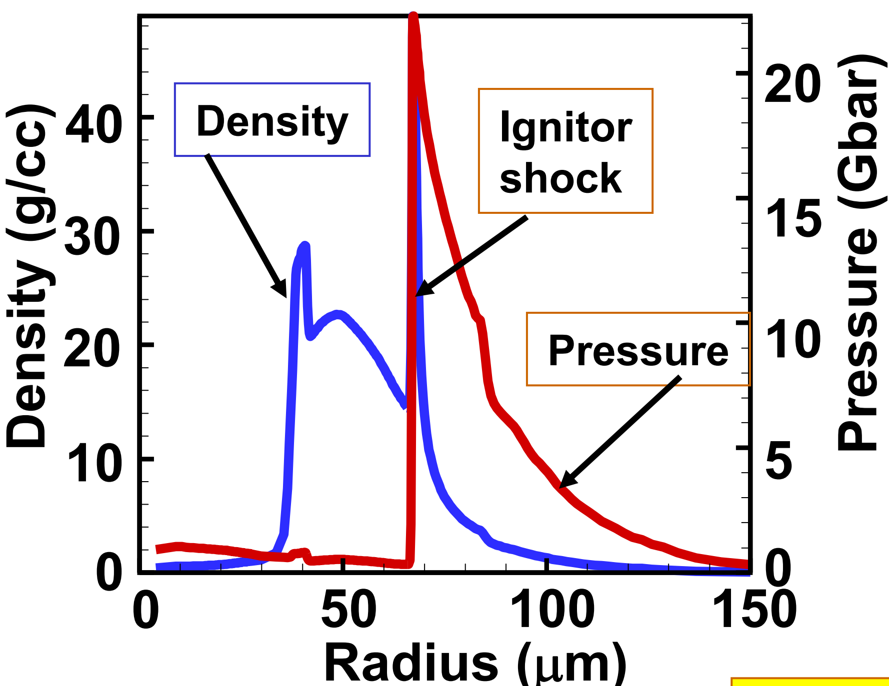


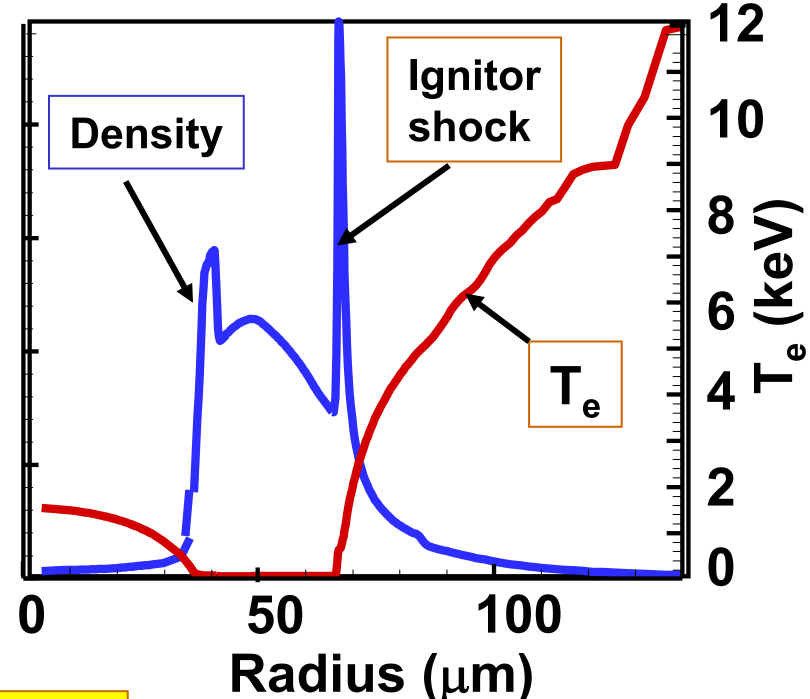


SHOCK FAST IGNITION

A spherically-convergent hot-particle driven shock is needed

SFI. Shock FAST ignition requires an ignitor shock much stronger than the return shock. OMEGA size targets can be ignited by a 13kJ shock





GAIN = 9

Shocks, fast electrons or a combination of the two can be used to improve the ignition condition and separate the fuel assembly from the ignition

- Implosions of massive shells at low velocity and low adiabat have been proven effective on OMEGA to assemble large amount of fusion fuel with high areal densities
- The ponderomative scaling for the fast electron energy leads to ultra-high electron energy not suitable for fast ignition.
- Shock ignition experiments on OMEGA show improvements in neutron yields well beyond the predictions of 1D codes
- A true 2-step ignition based on shock ignition requires a strong shock driven by particles (tens of kJ of 20-100keV electrons)