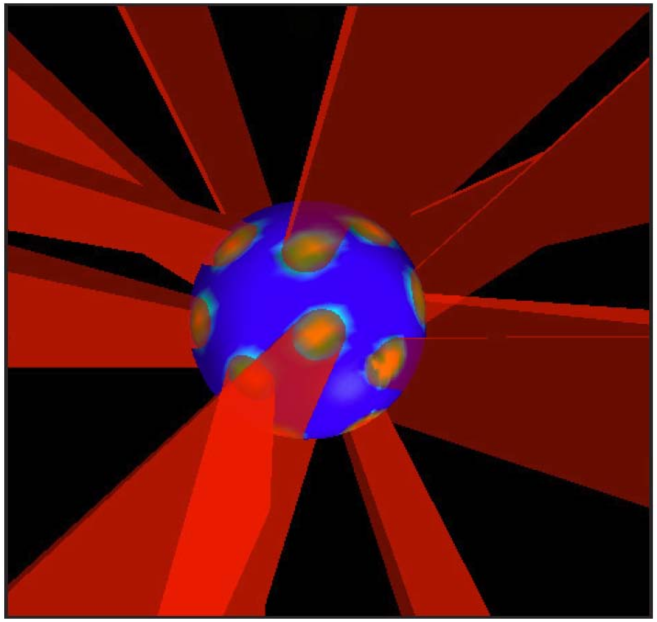
Overview of shock ignition



R. Betti
Fusion Science Center
Laboratory for Laser Energetics

Shock Ignition Workshop
March 8-10, 2011
Rochester, NY

I will show results from:

K. Anderson (LLE)
R. Nora (LLE)
C. Stoeckl (LLE)
W. Theobald (LLE)
J. Bates (NRL)
A. Schmitt (NRL)
M. Lafon (CELIA)
X. Ribeyre (CELIA)
G. Schurtz (CELIA)
S. Weber (CELIA)
V. Tykhonchuk (CELIA)
S. Atzeni (U. Rome)
J. Perkins (LLNL)
O. Klimo (CTU)
and others……

Outline

- The physics of shock ignition
- Target optimization
- 1D gain curves
- 2D simulations
- Experimental results

The puzzle of high gains: how to ignite low-velocity imploding targets

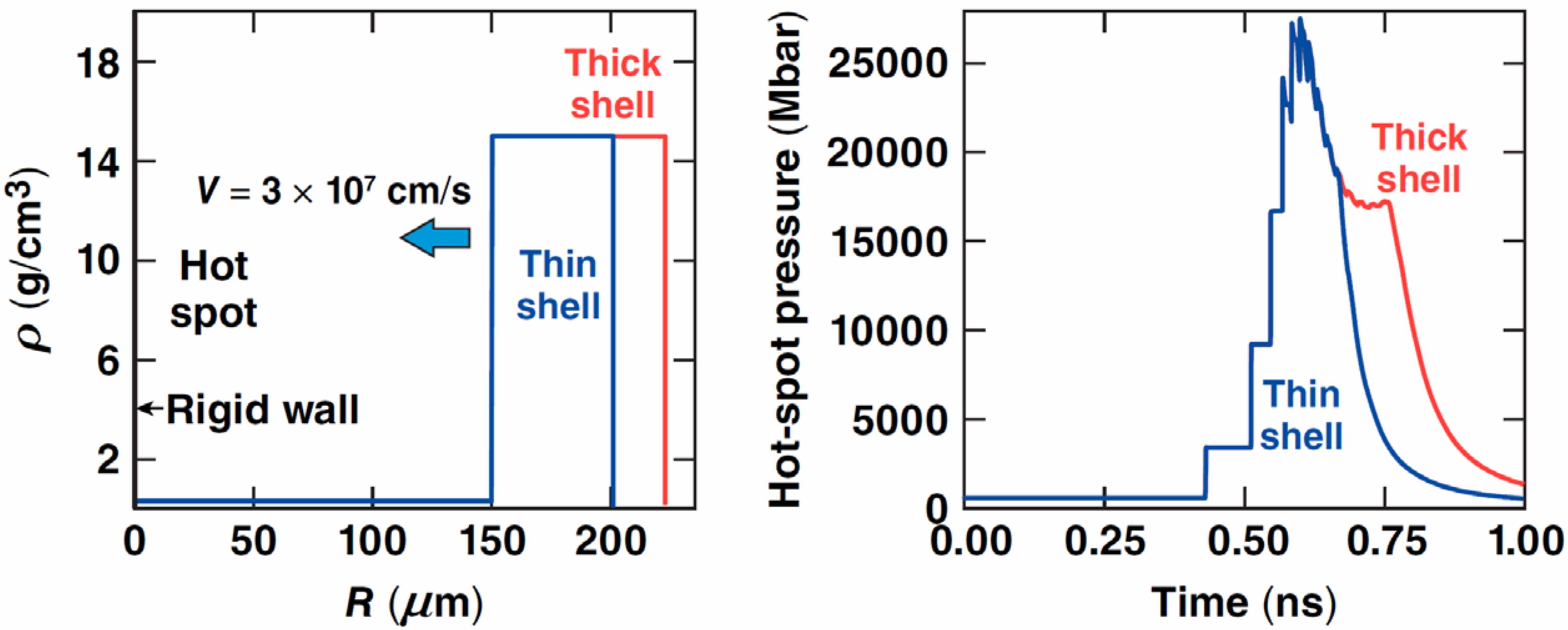
FSC UR LLE

- Thick shells (with large fuel mass) produce high gains if ignited
- Thick shells have good hydro-stability properties (because they are thick)
- For a fixed laser energy, thick shells have low implosion velocity
- Low implosion velocity leads to low hot spot pressure ($P \sim V_i^{2-3}$)
- Low pressure hot spots do no ignite ($P\tau > 30$ Gbar/ns)
- The energy required for ignition scales as $E \sim 1/P^{2-2.5}$

How do we ignite low-velocity implosions?

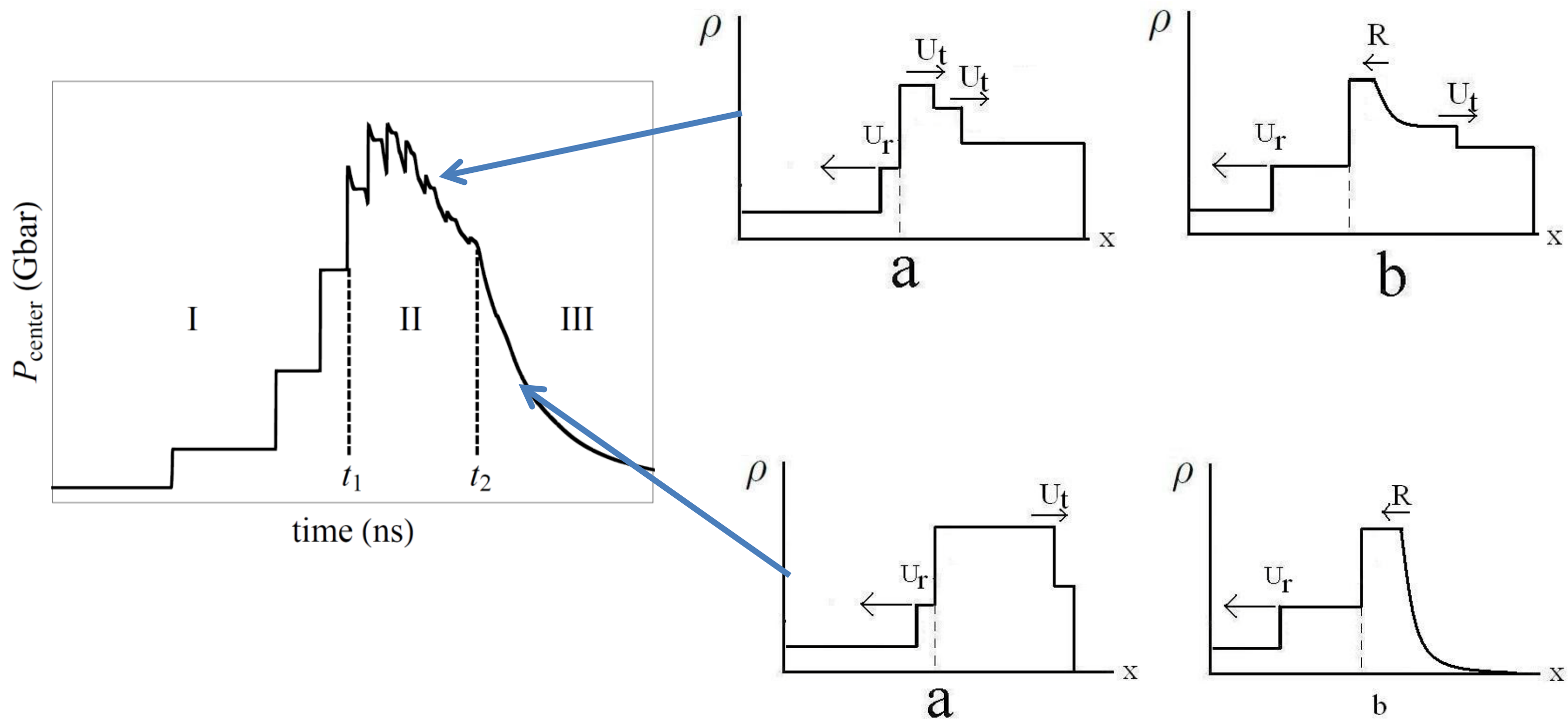
Raising the kinetic energy by thickening the shell does not increase the hot-spot pressure

Planar model of a compressible dense slab/shell compressing a low-density gas



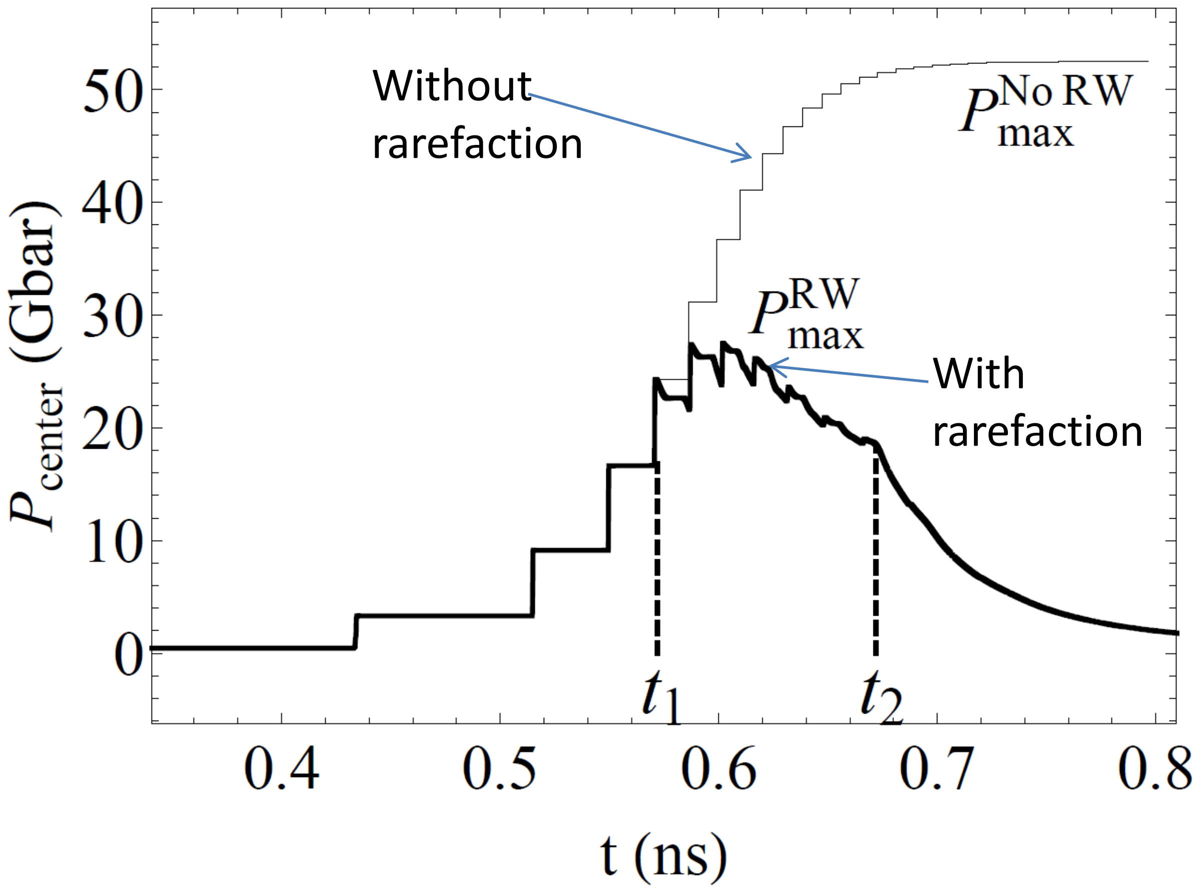
TC8240

Two different mechanisms related to rarefaction wave propagation limit the hot spot pressure



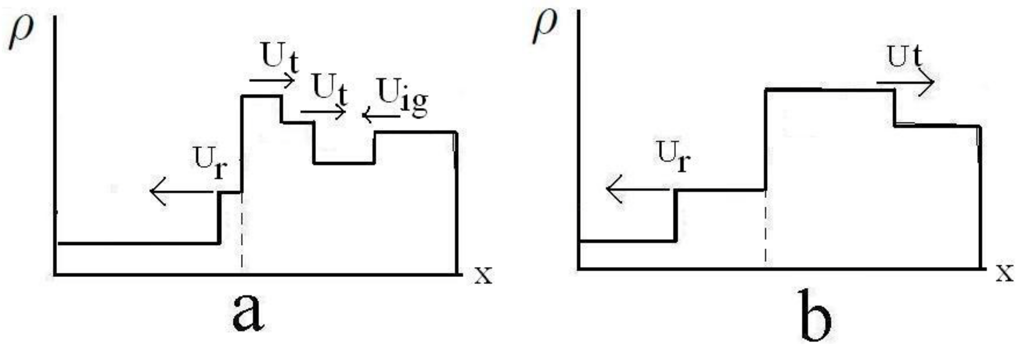
R. Nora and R. Betti, submitted to Phys. Plasmas

Without rarefaction waves, the peak hot spot pressure would be twice as high

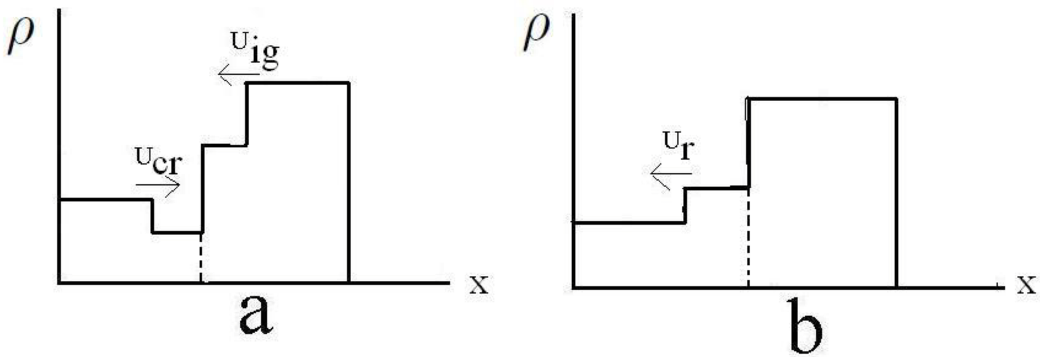


R. Nora and R. Betti, submitted to Phys. Plasmas

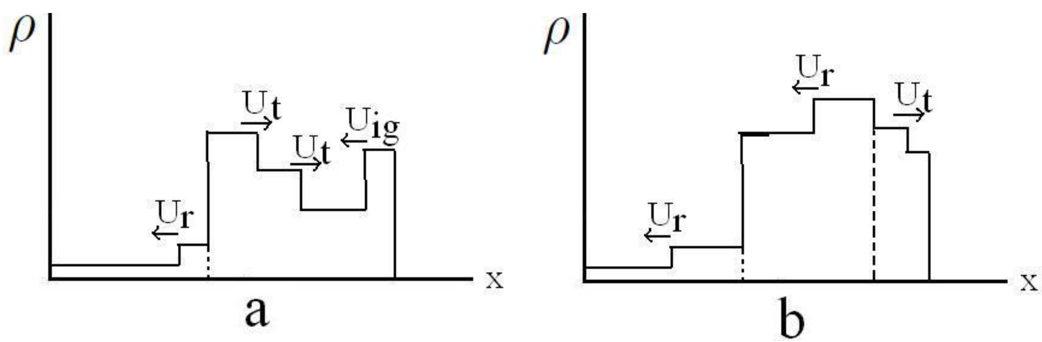
Late shocks can suppress rarefaction waves. There are three ways shocks can be launched.



No-rarefaction technique
(requires many highly-synchronized "weak" shocks)



No-transmission technique
(requires one moderate shock)

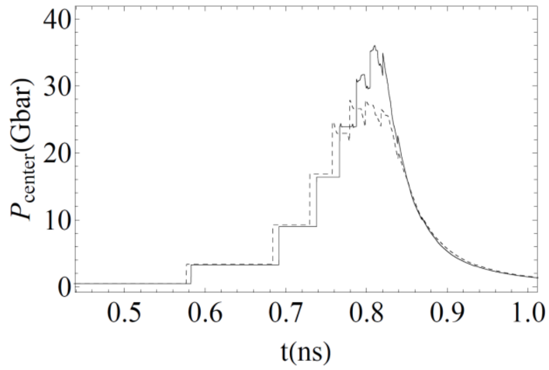


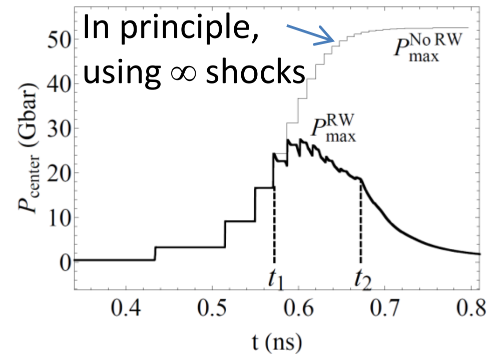
Re-shock technique
(requires one strong shock)

R. Nora and R. Betti, submitted to Phys. Plasmas

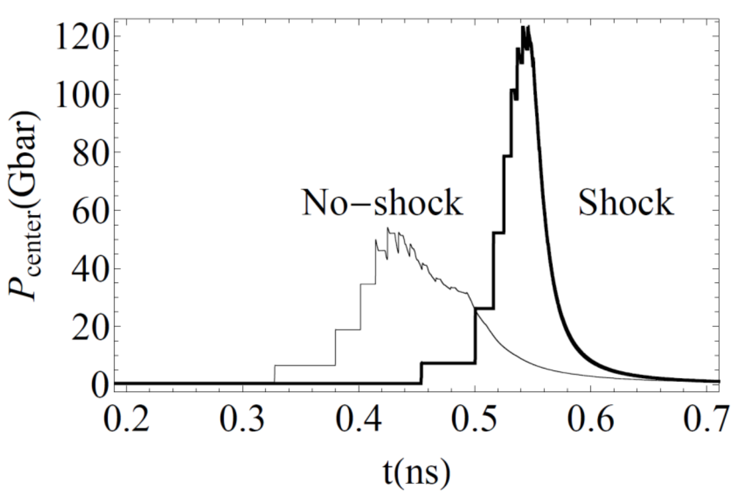
The enhancement in hot spot pressure varies for different techniques (total energy is kept constant)

No-rarefaction technique with two "weak" shocks

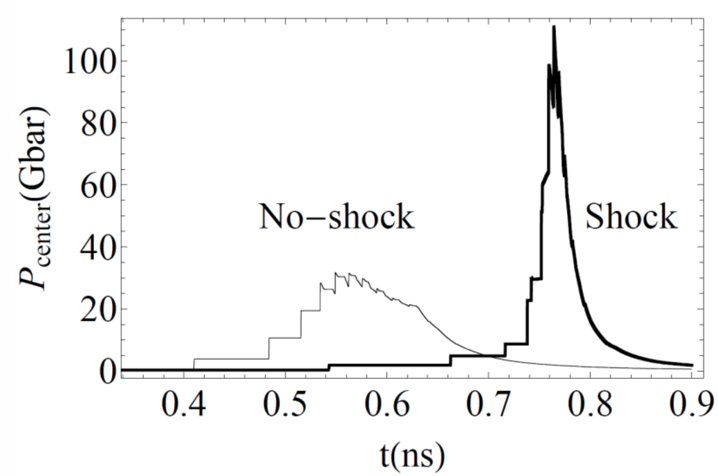




No-transmission technique with one shock



Re-shock technique with one shock (for a given shock strength)



R. Nora and R. Betti, submitted to Phys. Plasmas

The re-shock technique produces the highest hot spot pressure

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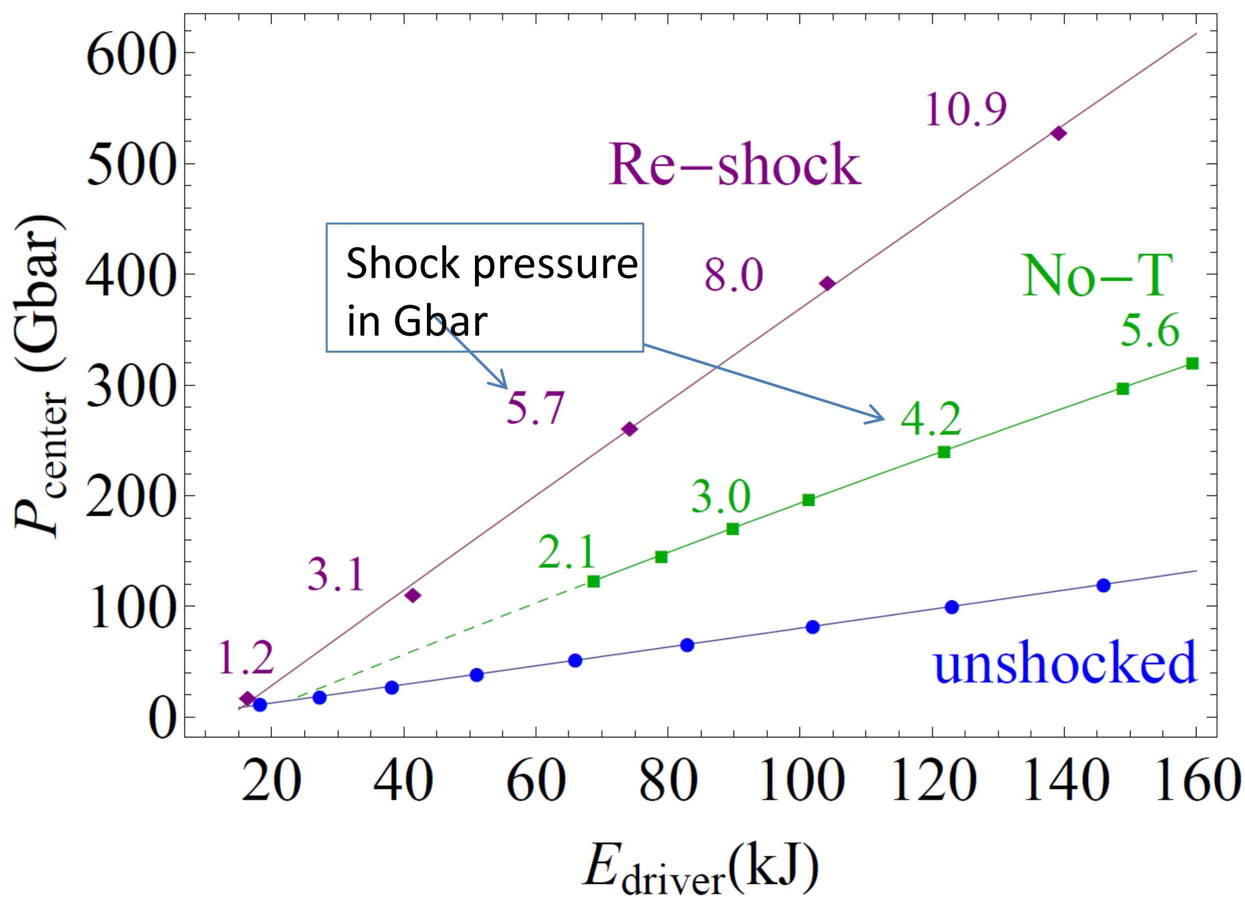

The shock pressure is high because of the planar geometry

R. Nora and R. Betti, submitted to Phys. Plasmas

In spherical geometry, convergence effects amplify the ignitor shock by about ten fold

FSC

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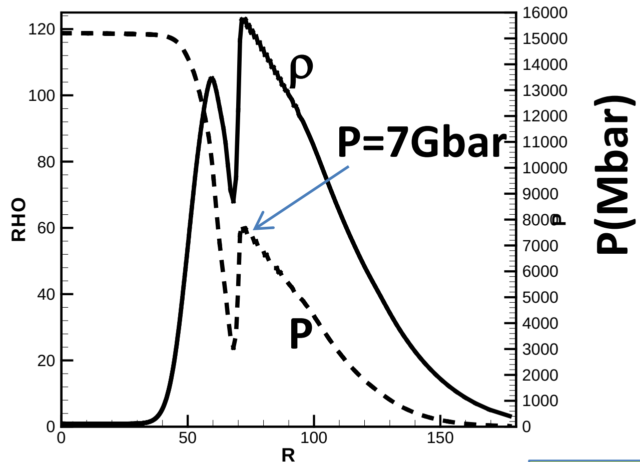
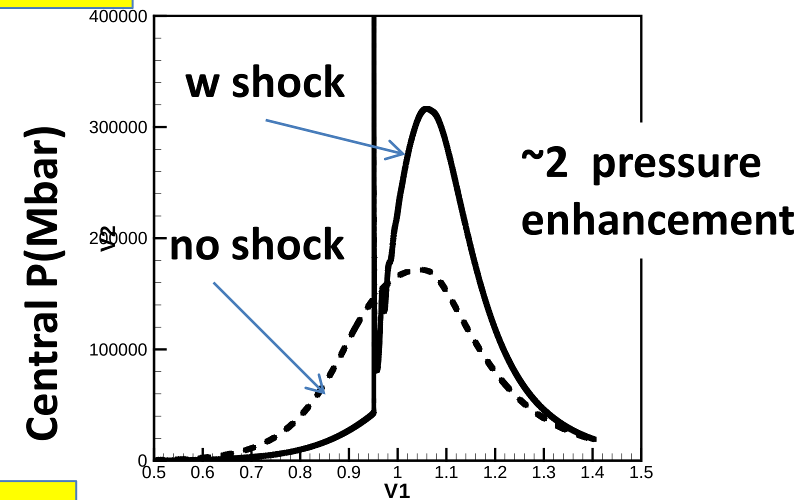
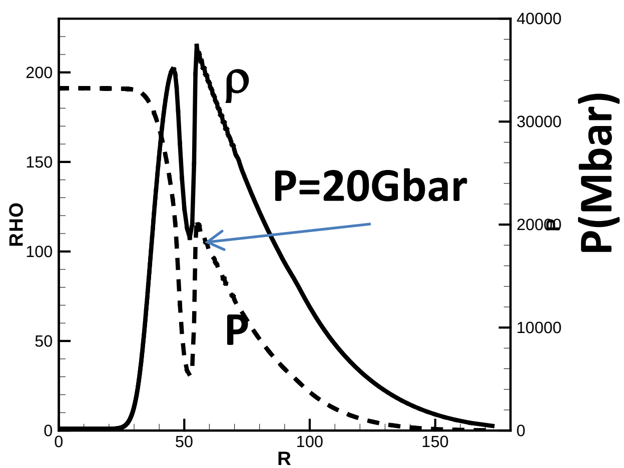
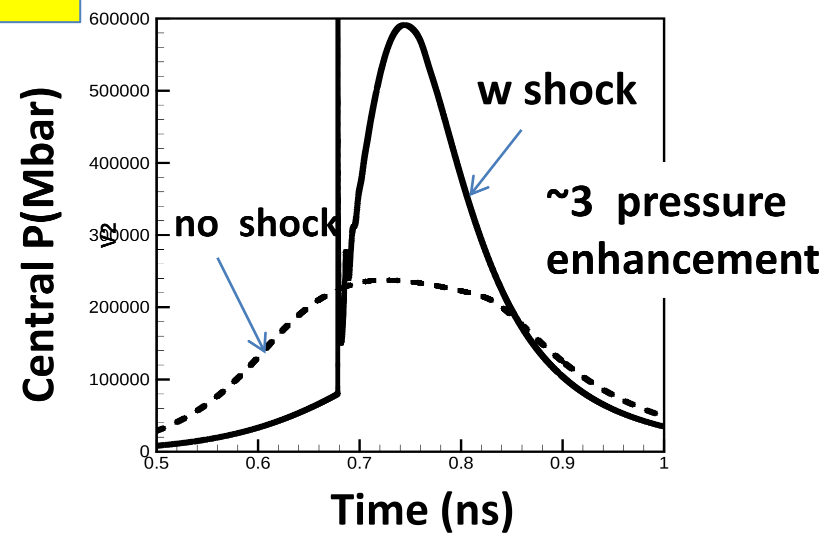
500Mbar Shock





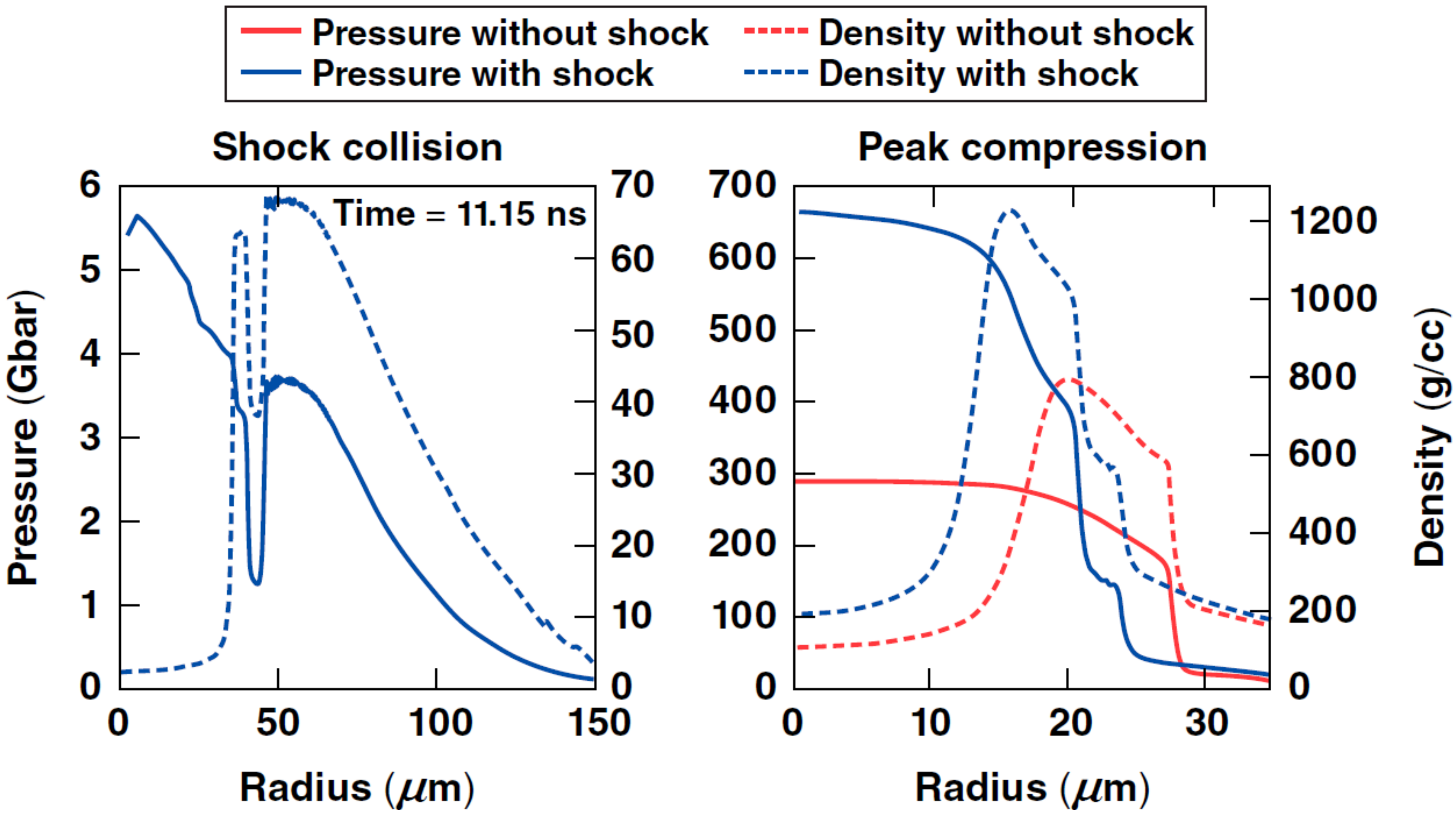
2Gbar Shock





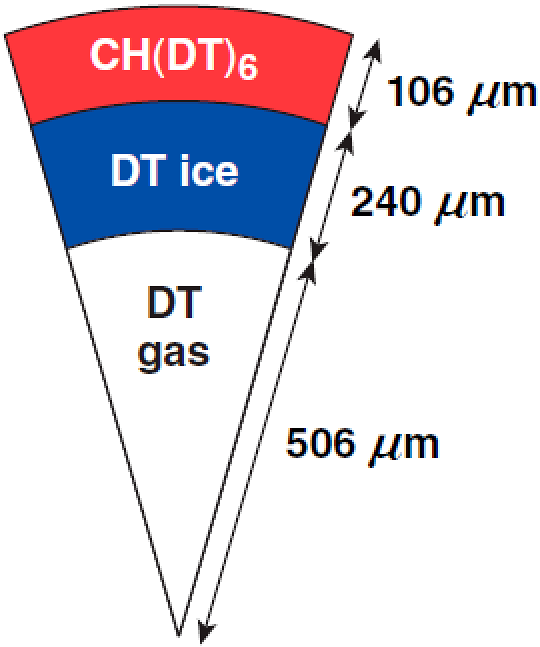
LILAC agrees with the predictions of the simple model for both shock amplification and pressure enhancement

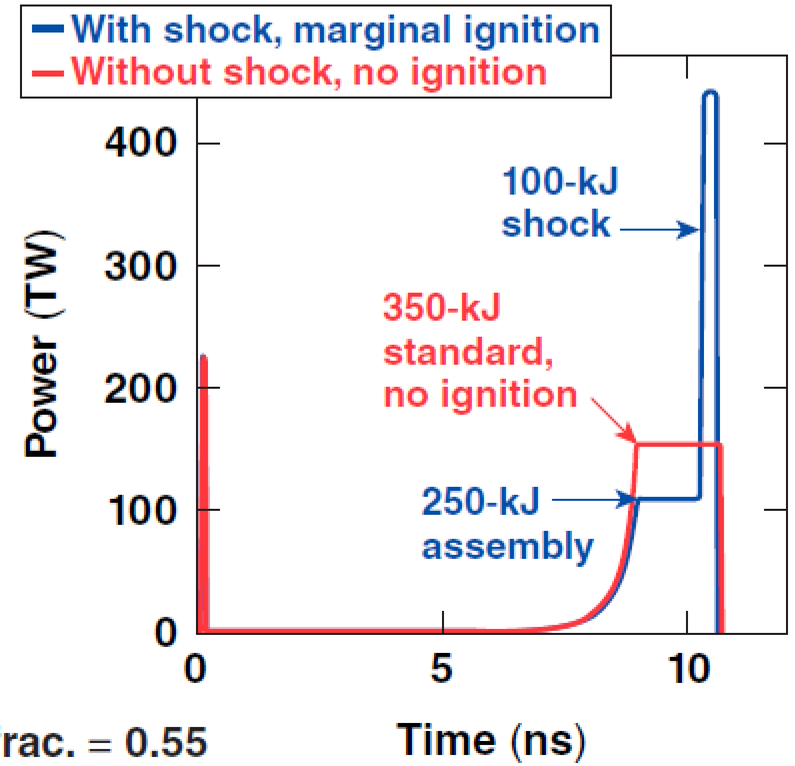
300-400Mb Shock



Optimal SI targets are wetted-foam shells (in the absence of hot electron pre-heat)

E_L = 350 kJ UV light, $V_i = 2.4 \times 10^7$ cm/s, $\alpha = 1$, $\lambda_L = 0.35\ \mu m$

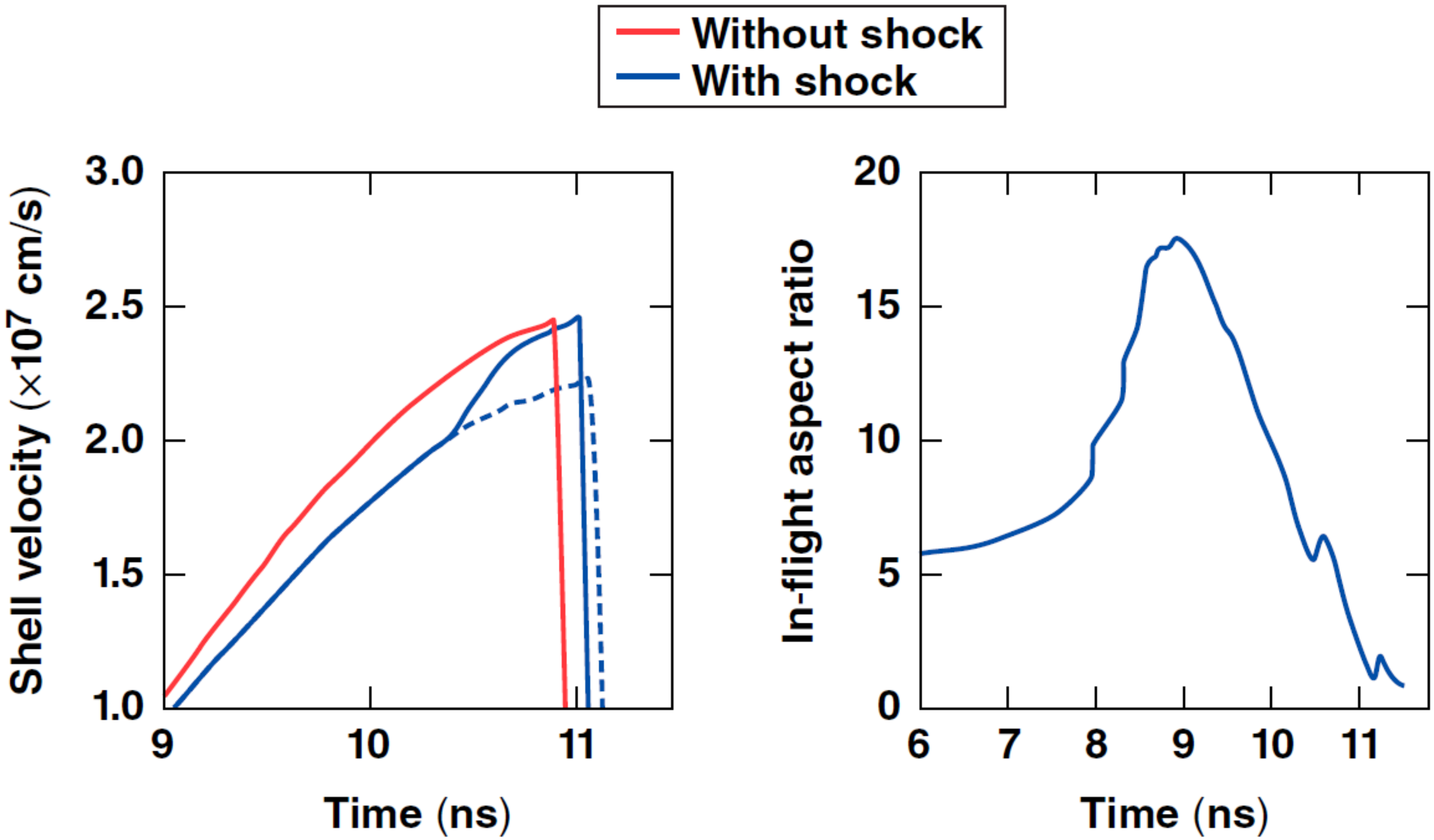




- Standard pulse shape abs. frac. = 0.55
- Shock-ignition pulse shape abs. frac. = 0.50

TC7821

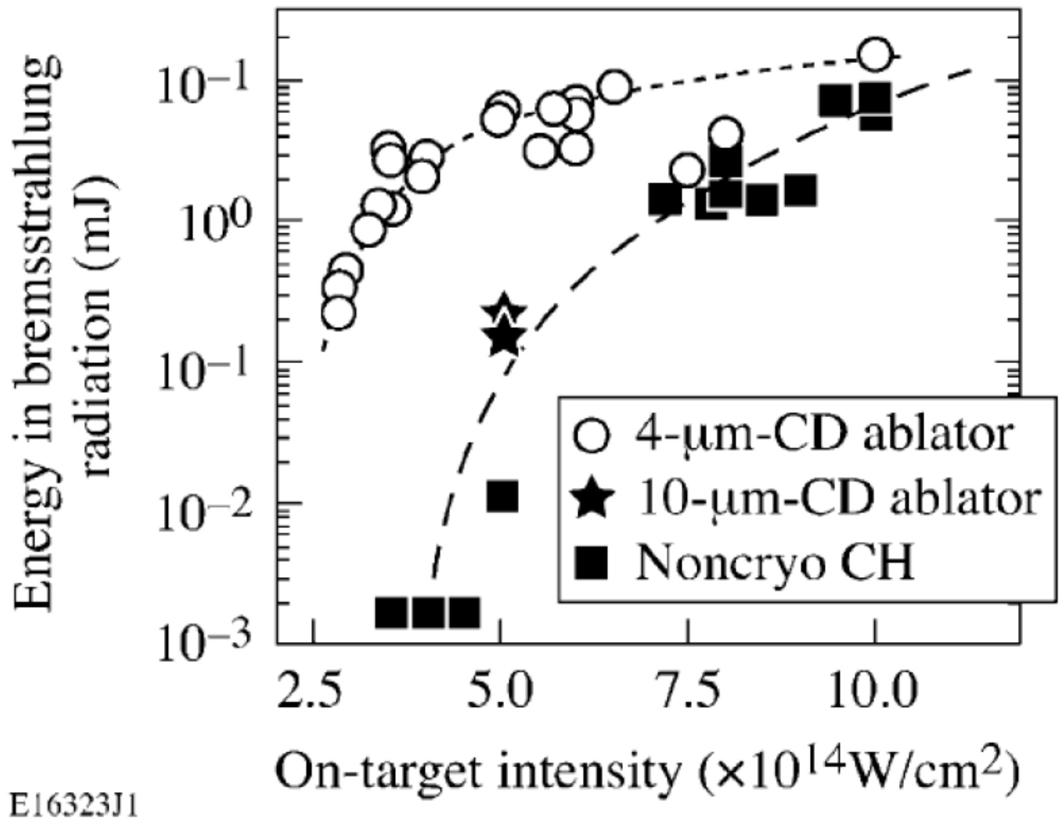
SI wetted-foam target have low IFARs and good stability properties



E-foldings of growth for most dangerous (kd = 1) RT modes ~ 4

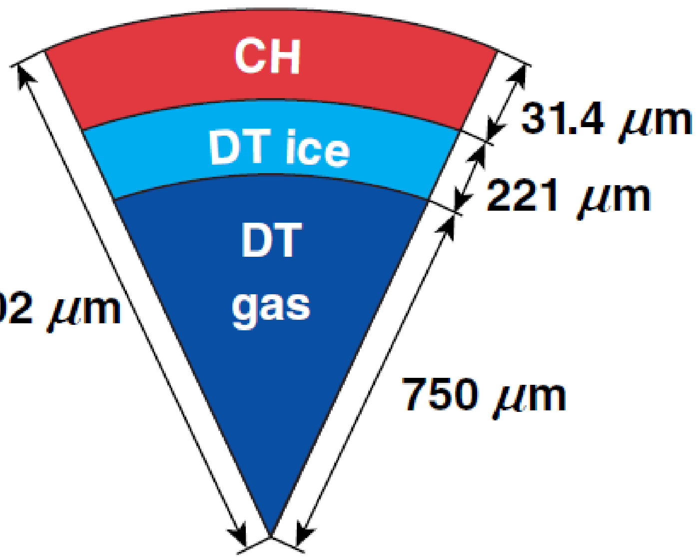
TC7869

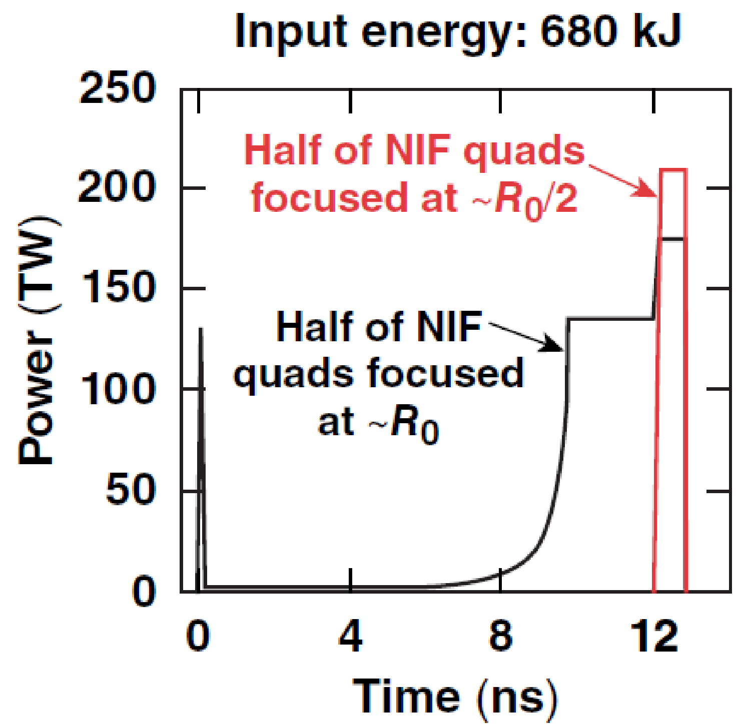
OMEGA experiments show high hot-electron signals for hydrogenic ablators



Sangster et al, PRL 2008

Shock-ignition targets with CH ablators have higher IFARs. Hydrodynamic instabilities can be a concern.





Gain (1-D)	70
ρR (g/cm^2)	2.6
V_{imp} (μm/ns)	300
$IFAR_{2/3}$	30

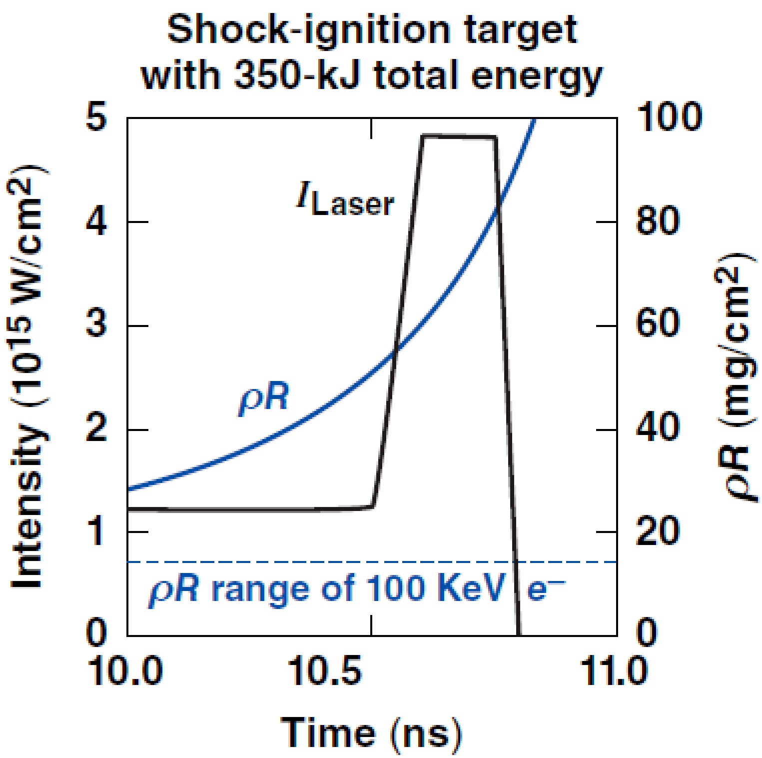
1-D beam profiles approximate polar drive.*

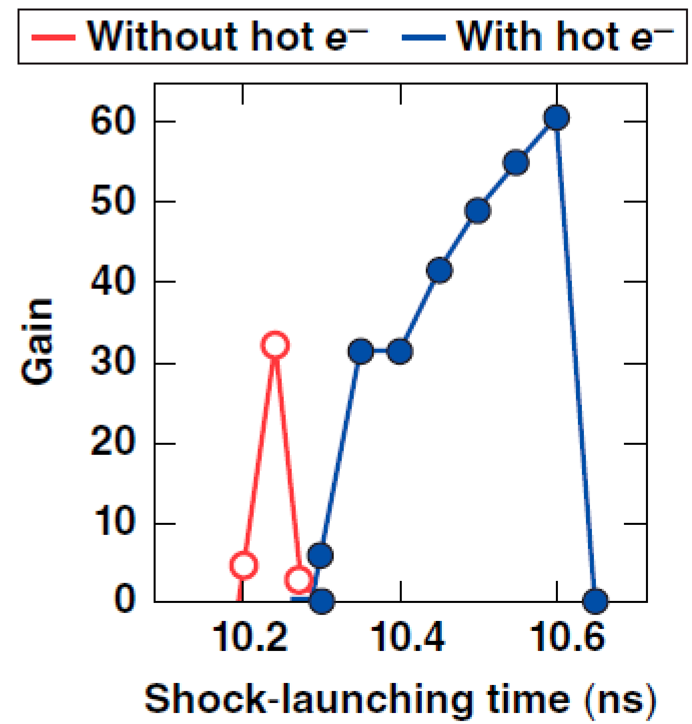
$$IFAR_{2/3} = \frac{R}{\Delta R} \text{ at } R = \frac{2}{3} R_0$$

TC9109

K. Anderson (this workshop)

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





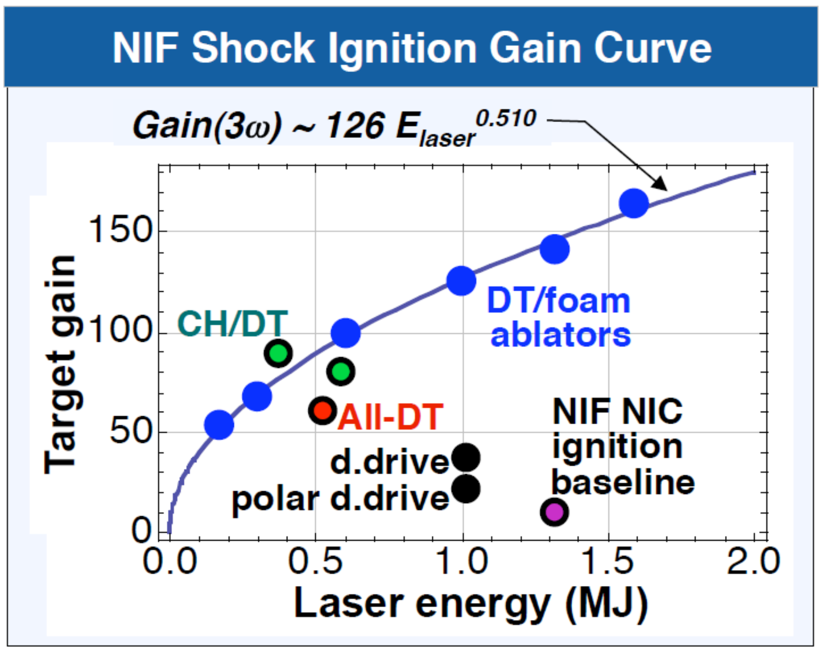
Hot e⁻ with Maxwellian T_{hot} = 150 keV, E_{hot} = 17% of spike energy, treated using a multigroup diffusion model*

TC7870

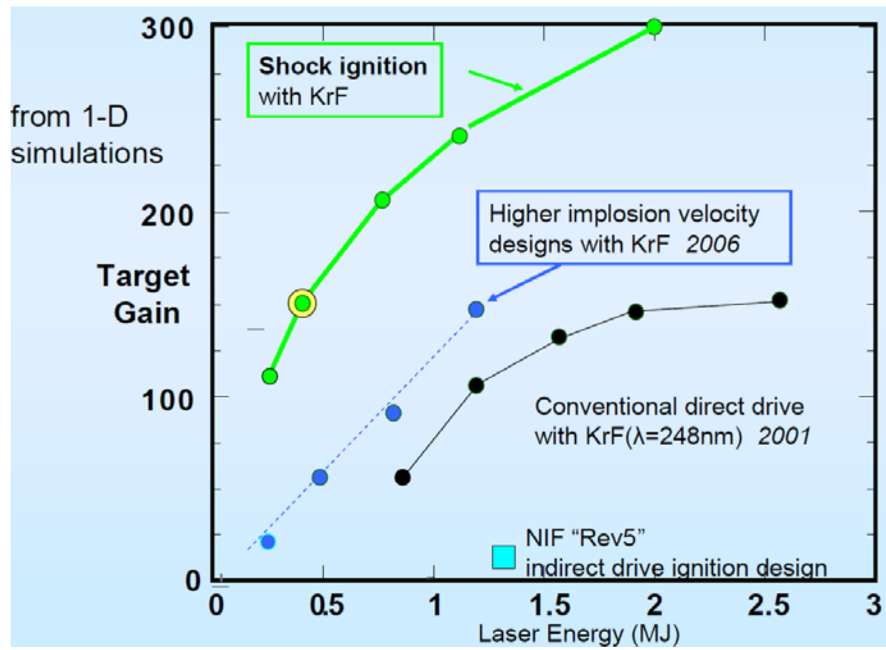
*J. Detettrez and E. B. Goldman, LLE, Univ. of Rochester, Rochester, NY, LLE Report No. 36 (1976).

Also see K. Anderson (this workshop)

Gain curves for shock ignition look impressive but need to assess the sensitivity to preheat (during the main pulse) and (for CH targets) to laser imprinting.



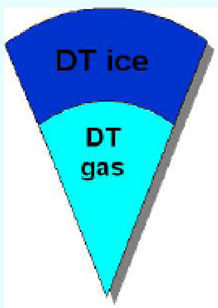
JL Perkins (LLNL)

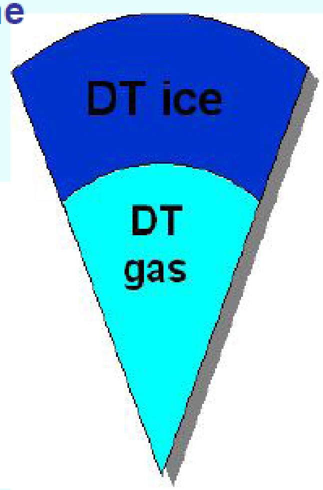


A. Schmitt (NRL)

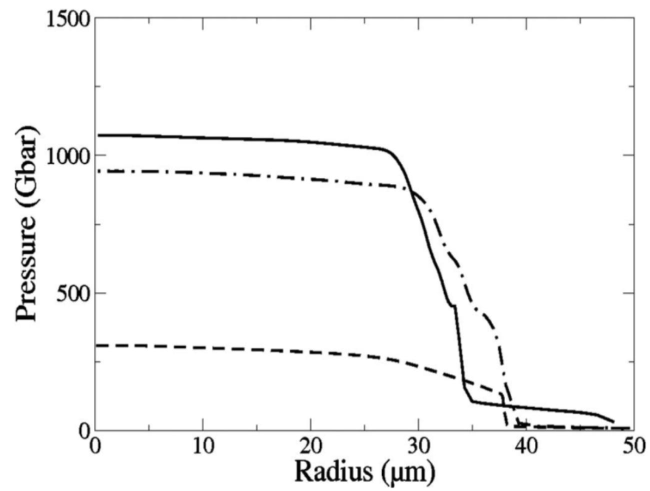
3-fold pressure amplifications are found for HiPER targets. Gains curves are derived by hydro-equivalent scaling

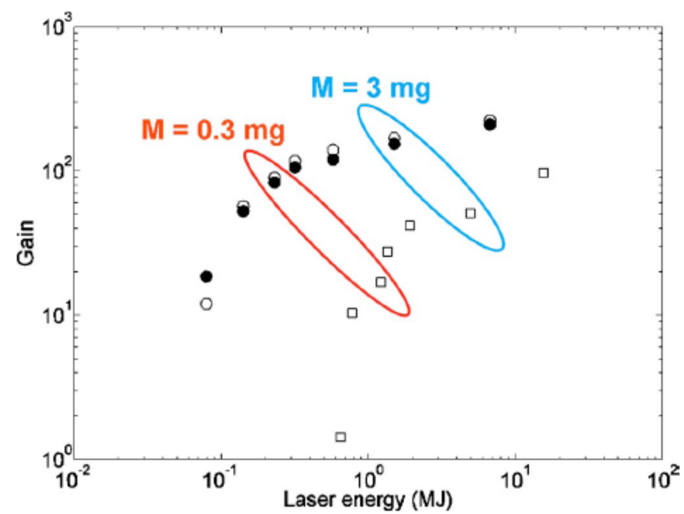
The HiPER target can be rescaled to the reactor size





M_f = 0.3 mg	M_f = 3.0 mg
ρR = 1.34 g/cm2	ρR = 2.12 g/cm2
V_{imp} = 285 km/s	V_{imp} = 265 km/s
E_L = 0.25 MJ	E_L = 1.5 MJ
G = 90	G = 170
E_L = 1.2 MJ	E_L = 5.0 MJ
G = 17	G = 50



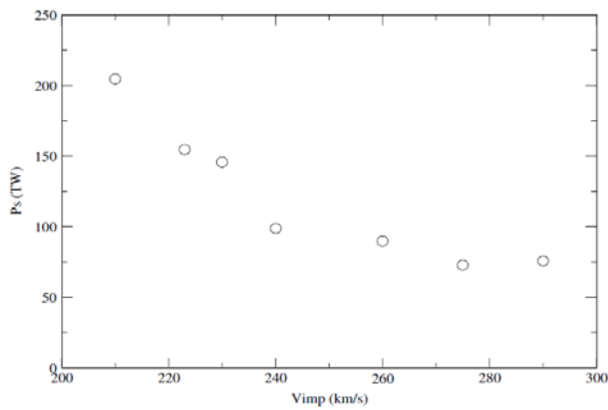


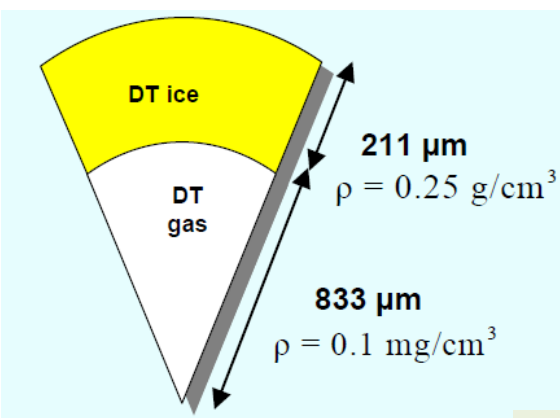
Lafon, Ribeyre, Schurtz, Phys. Plasmas 17, 052704 (2010)

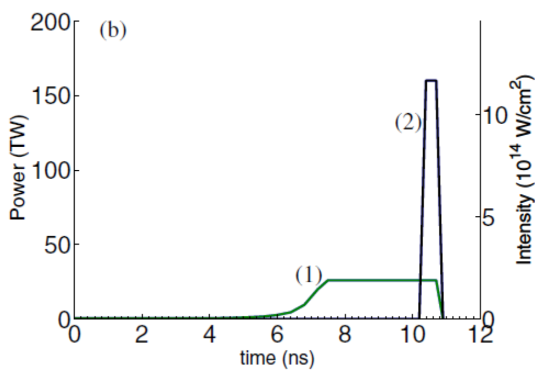
The spike power and launching time are optimized for HiPER shock ignition targets

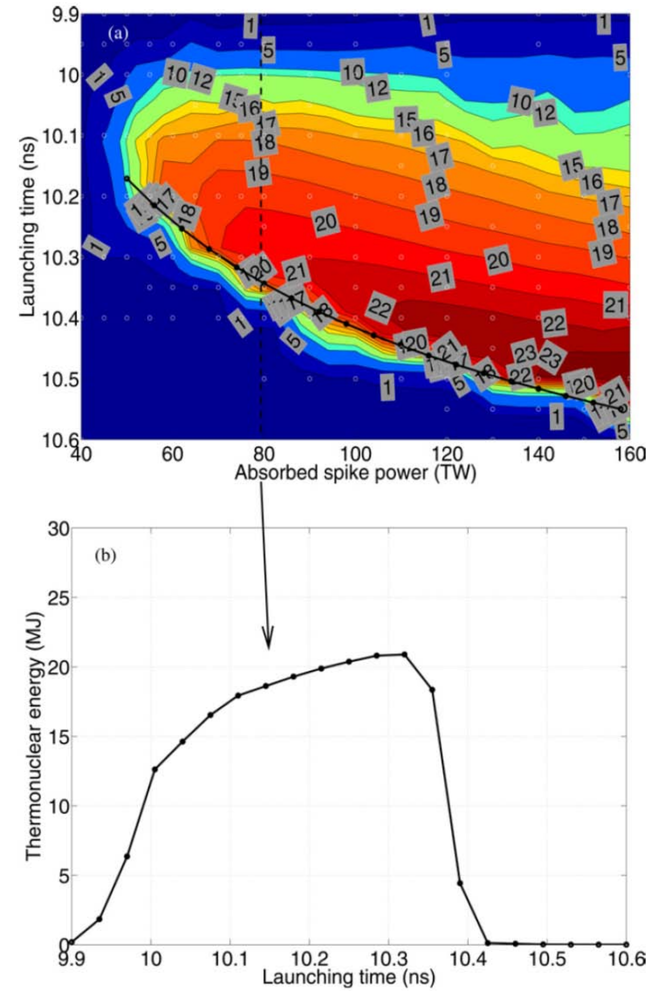
HiPER shock ignition target

Initial aspect ratio	$\simeq 5$
In-flight aspect ratio	$\simeq 35$
In-flight mass (mg)	$\simeq 0.28$
Implosion velocity ($\mathrm{km\,s^{-1}}$)	$\simeq 290$
Adiabat parameter	$\simeq 1.0$
Peak density ($\mathrm{g\,cm^{-3}}$)	$\simeq 625$
Peak areal density ($\mathrm{g\,cm^{-2}}$)	$\simeq 1.50$



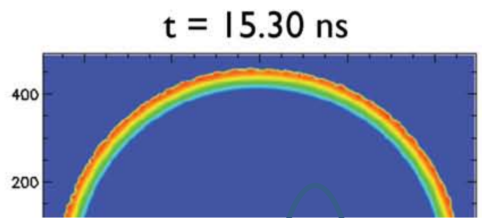




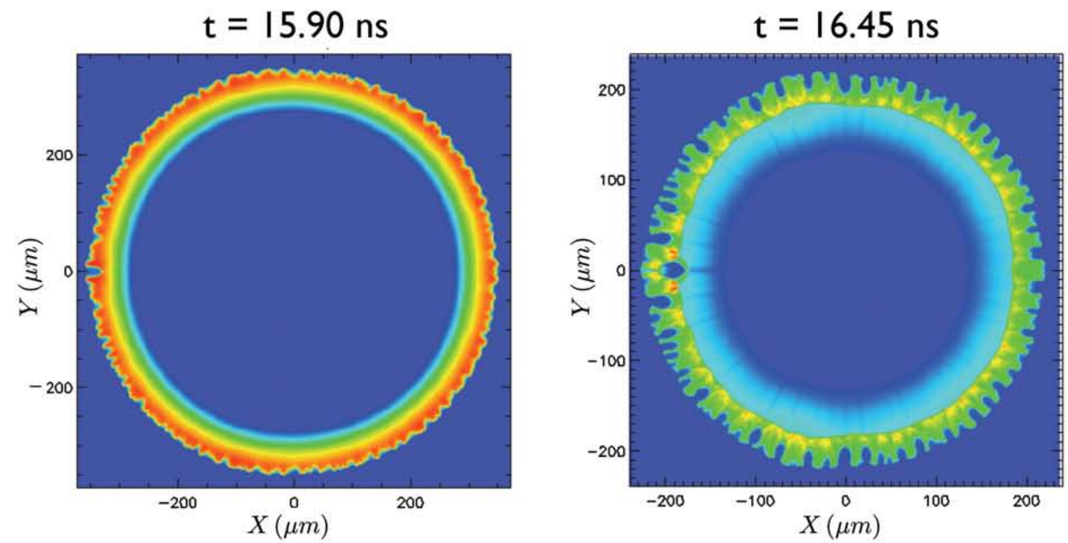


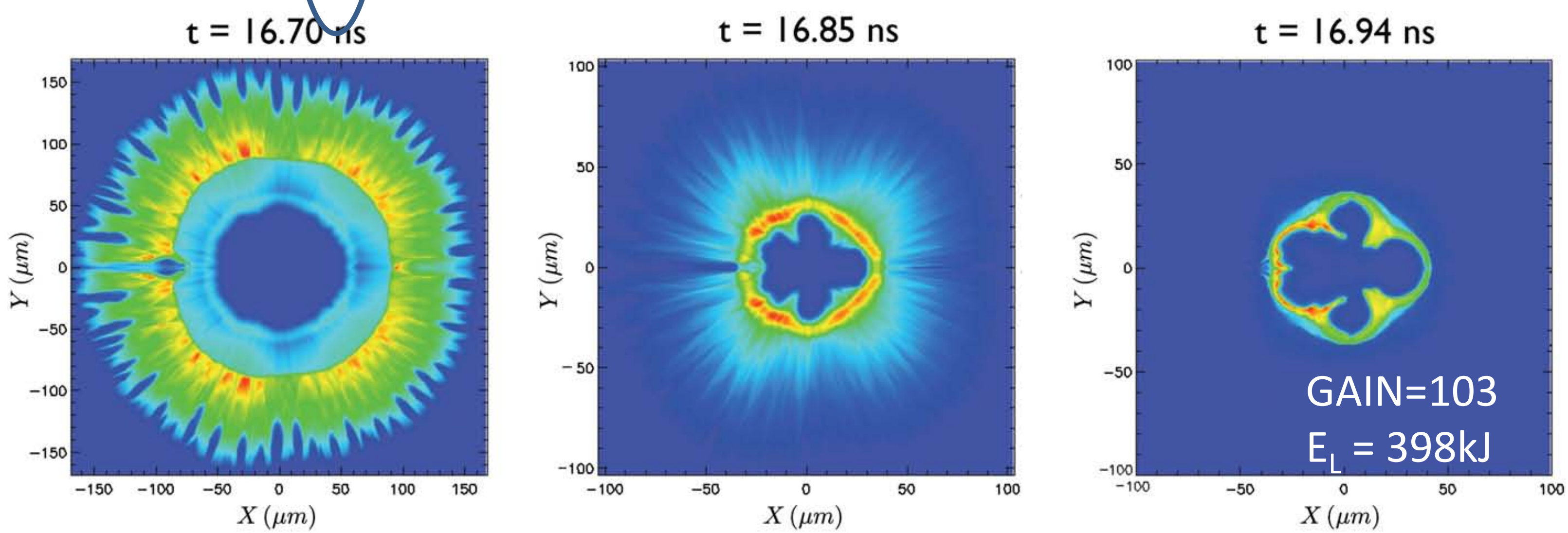
Ribeyre, Schurtz, Lafon, Galera, Weber, PPCF 51, 015013 (2009)

Comprehensive 2D simulations of SI KrF targets, with zooming are carried out by the NRL group



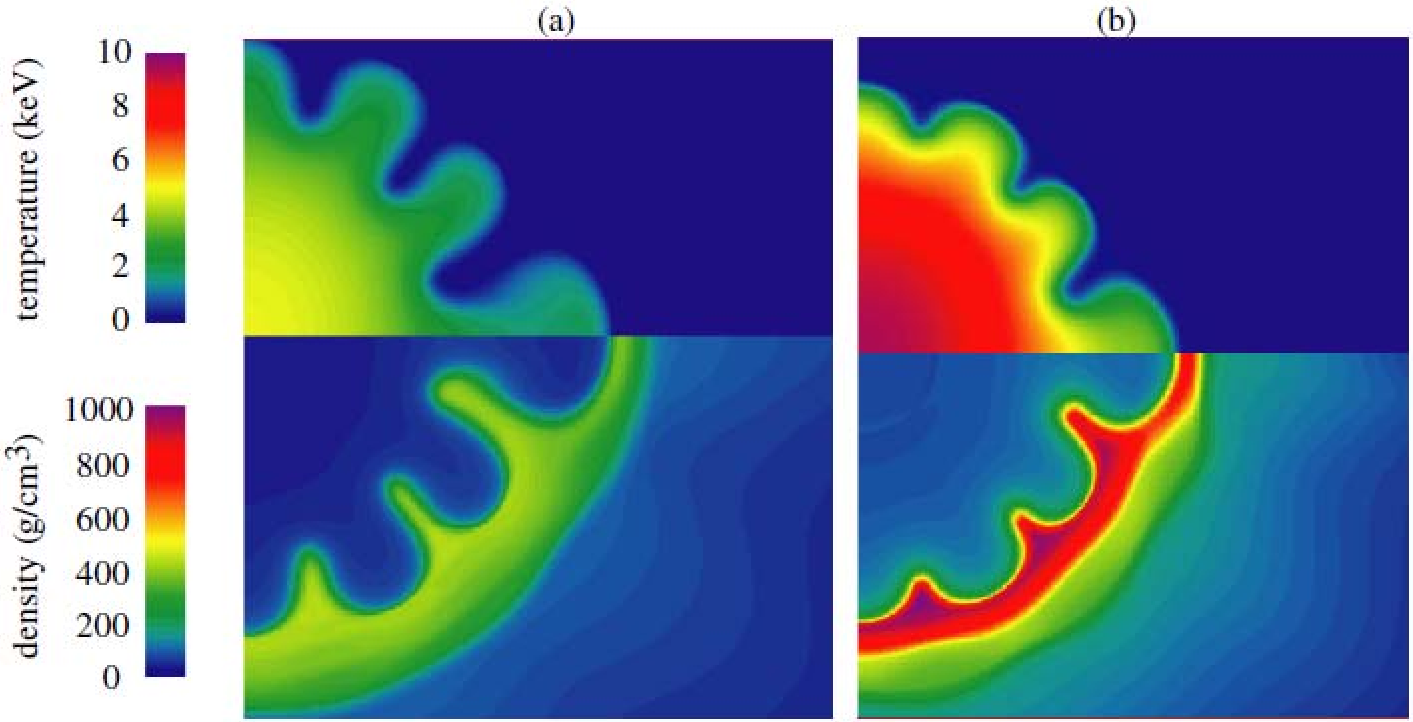
Parameter	Scale-1	Scale-2	Scale-5
Pellet mass (mg)	0.58	1.17	2.89
R_1 (μm)	512	640	871
R_2 (μm)	237	300	407
R_3 (μm)	108	136	177
Initial aspect ratio	2.48	2.47	2.49
Convergence ratio	64	65	63
Peak velocity (km/s)	286	260	220
Laser energy (kJ)	243	398	727
Highest gain	101	143	210





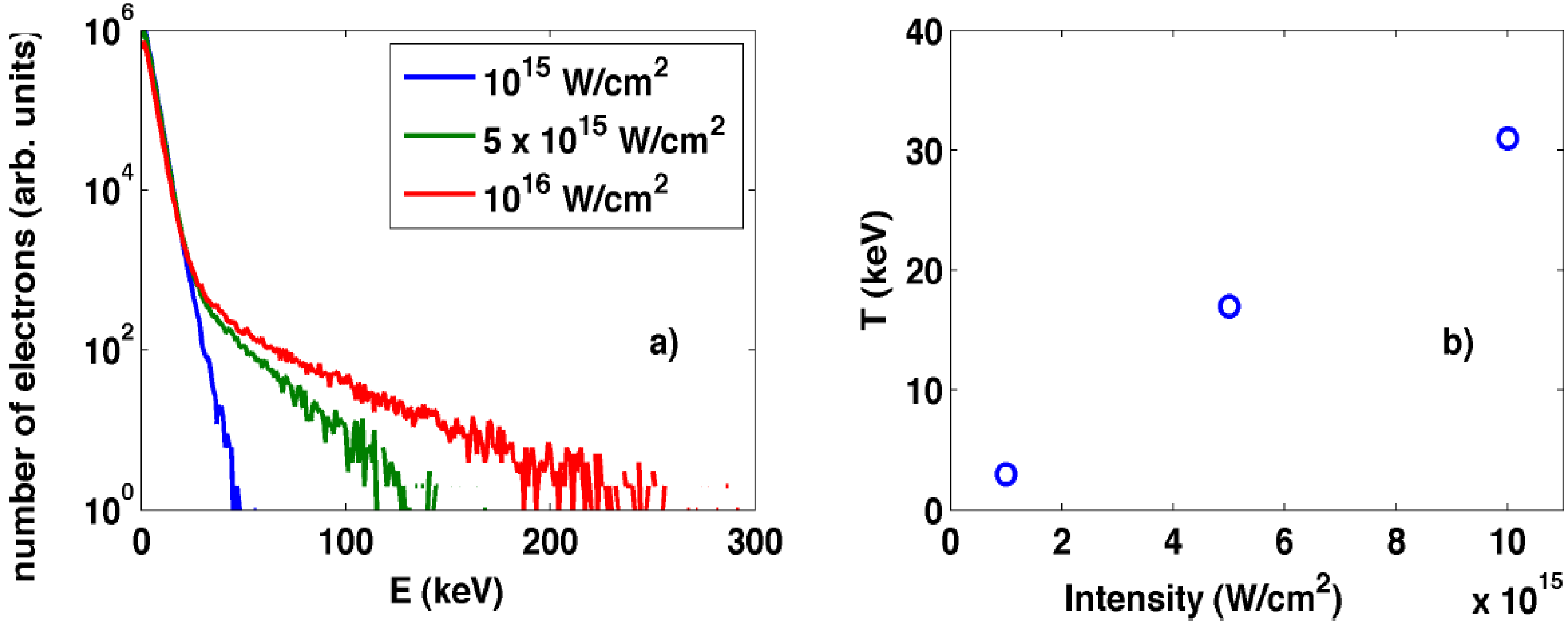
Bates, Schmitt, Fyfe, Obenschain, Zalesak, High Energy Den Phys 6, 128 (2010)

Ignitor-return shock collision seems to reduce the deceleration RTI growth before ignition



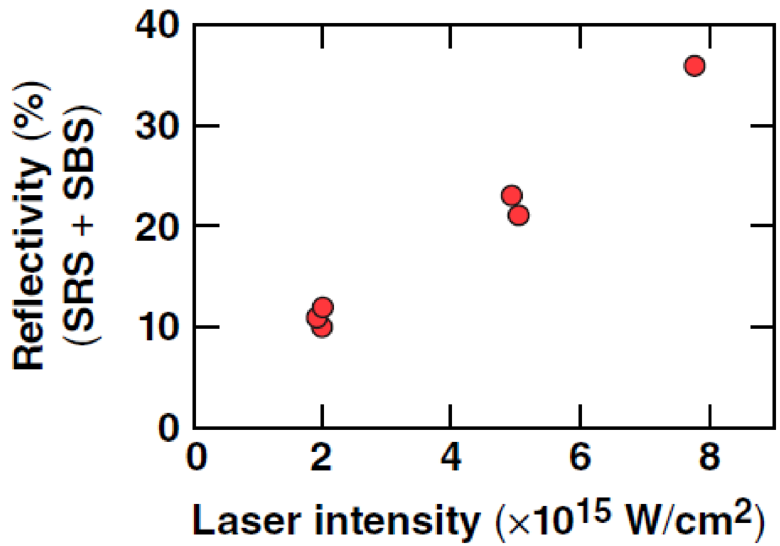
Atzeni, Davies, Hallo, Honrubia, Maire, Olazabal, Feugeas, Ribeyre, Schiavi, Schurtz, Breil, Nicolai, Nucl. Fusion 49, 055008 (2009)

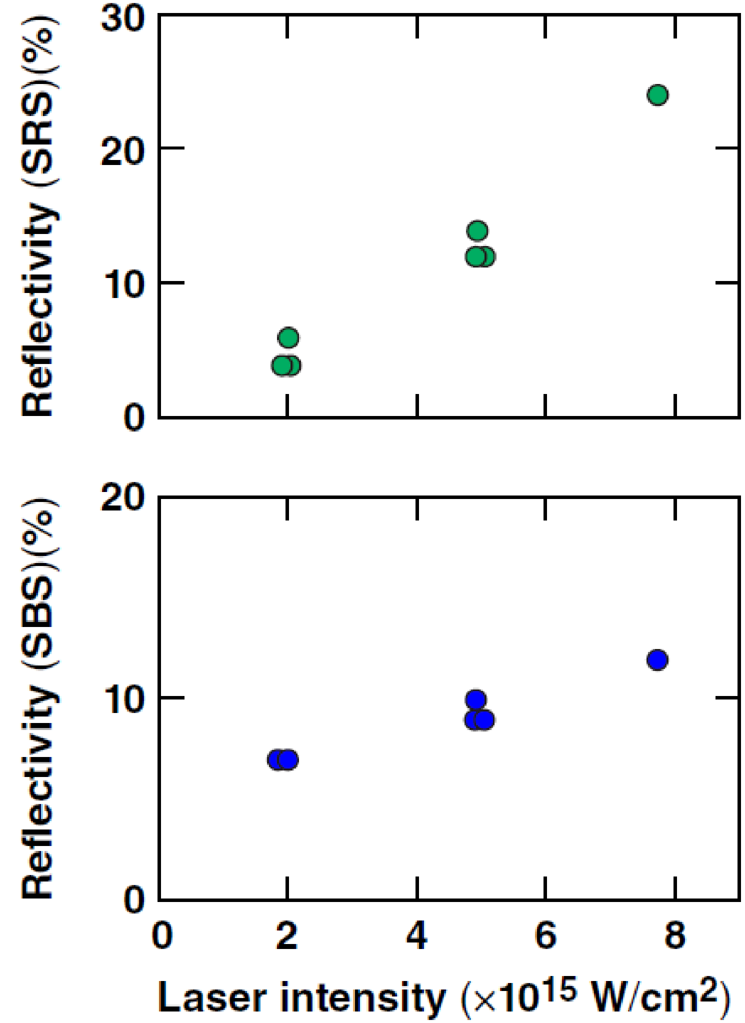
1D PIC simulations at SI-spike relevant intensities show low-temperature hot electrons with an energetic tail



Klimo, Weber, Tikhonchuk, Limpouch, Plasma Phys Cont Fus 52, 055013 (2010)

Up to 35% of the shock-beam laser energy is lost due to backscatter. $T_{hot} \sim$ 45keV



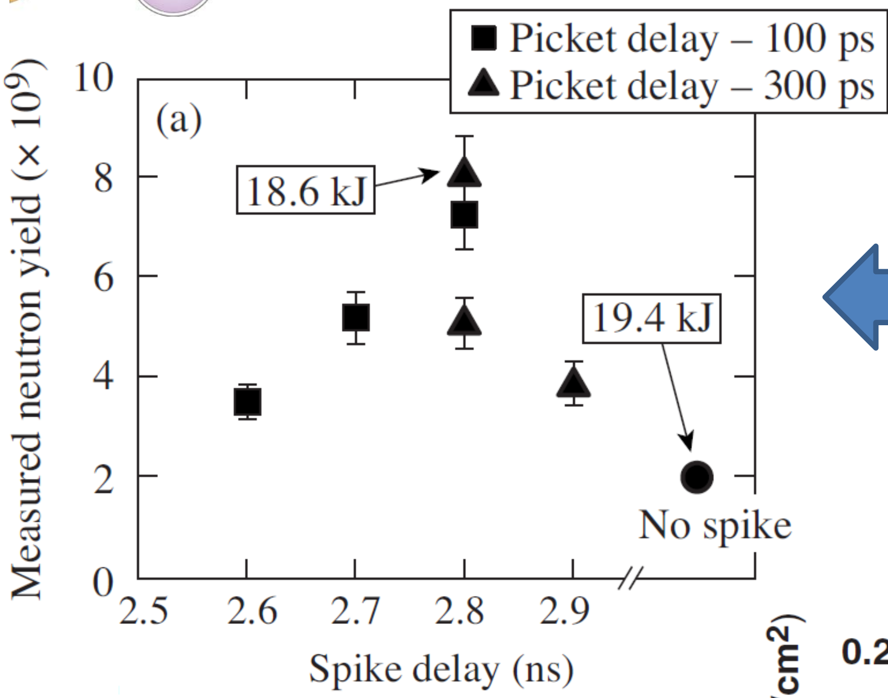


- No measurable signal of the 3/2 harmonic
- SRS dominates back reflection at highest intensity
- SBS reflection is relatively stable at ~10%

E18435

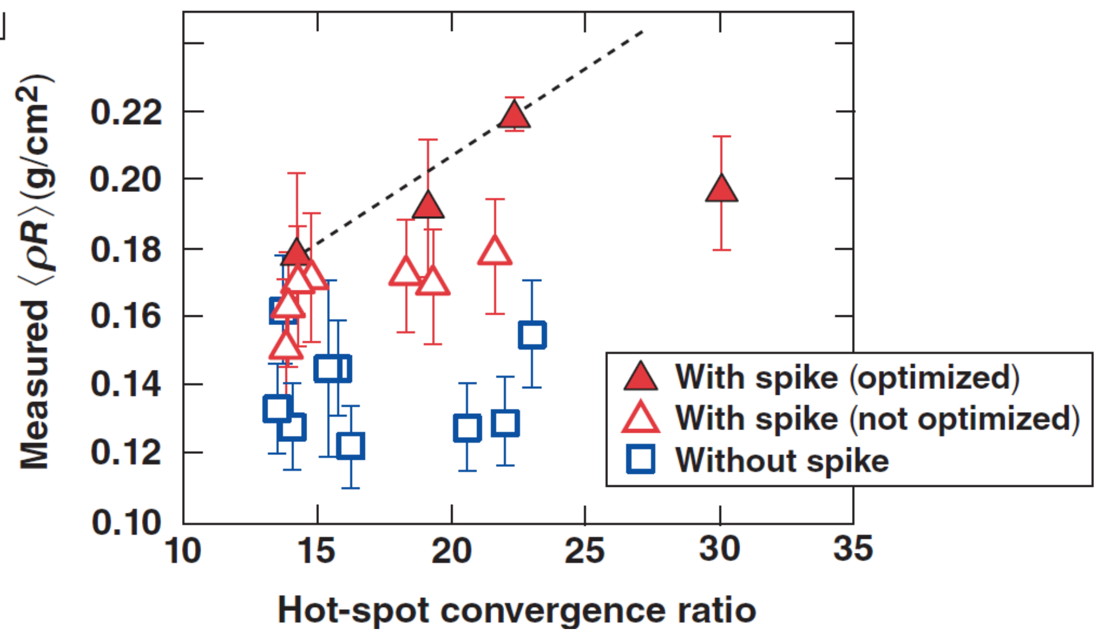
C. Stoeckl, APS 2009; W. Theobald et al, PPCF 51, 124052 (2009);

Higher neutron yields and areal densities are measured in shock ignition experiments using thick CH targets



Neutron yields:
Compare SI and CHS targets,
40 µm CH shells filled with
25 atm D2 gas

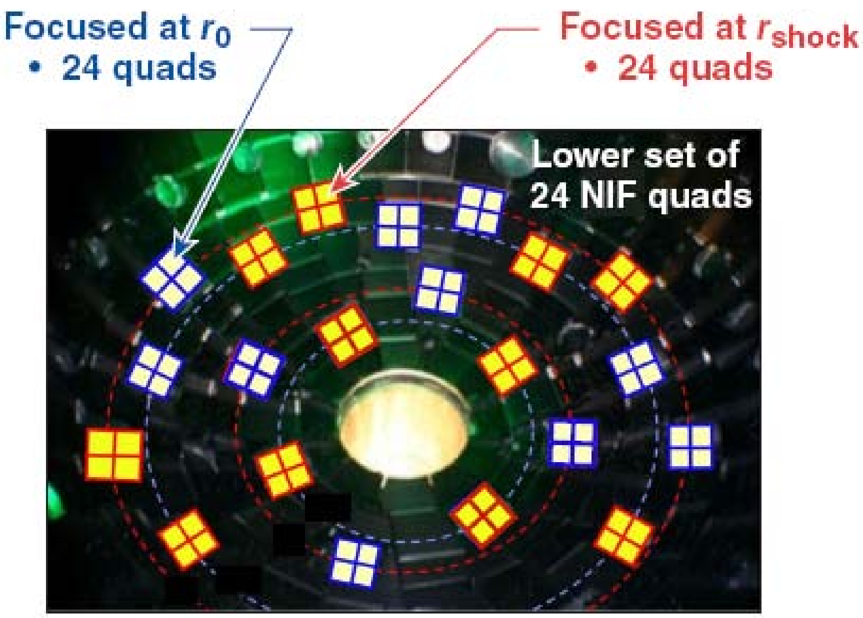
Areal densities:
Compare SI and CHS targets
Varying fill pressures



W. Theobald et al,
Phys Plasmas 15, 056306 (2008)

Beam pointing schemes are being explored for Polar Drive Shock Ignition on the NIF

- **Focusing separate shock beams at a smaller radius late in time allows better coupling of energy to the target.**
- **A scheme with split quads would allow best irradiation uniformity on target, but requires time-consuming "rewiring" of NIF seed pulses.**
- **Another scheme employing full quads, half for the main drive and half for the shock pulse was recently proposed[*] by Steve Craxton**



***Craxton, et al., APS-DPP 2010**

Conclusions

Significant progress has been made in the past two years, but there are still important issues to be resolved for the validation of shock ignition

- Need to demonstrate the generation of >300Mb shock waves in long density scalelength plasmas

- Need to demonstrate that hot electrons (mostly from TPD) during the main pulse can be controlled

- Need to demonstrate that the hot electrons above 100keV during the intensity spike do not preheat the capsule

- Need to demonstrate hot-spot integrity at the high convergence ratios typical of shock ignition