Overview of the Current Status of Shock Ignition

P. W. McKenty
University of Rochester
Laboratory for Laser Energetics

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Workshop discussions focused on target design and understanding the effects of LPI on target performance

Target design

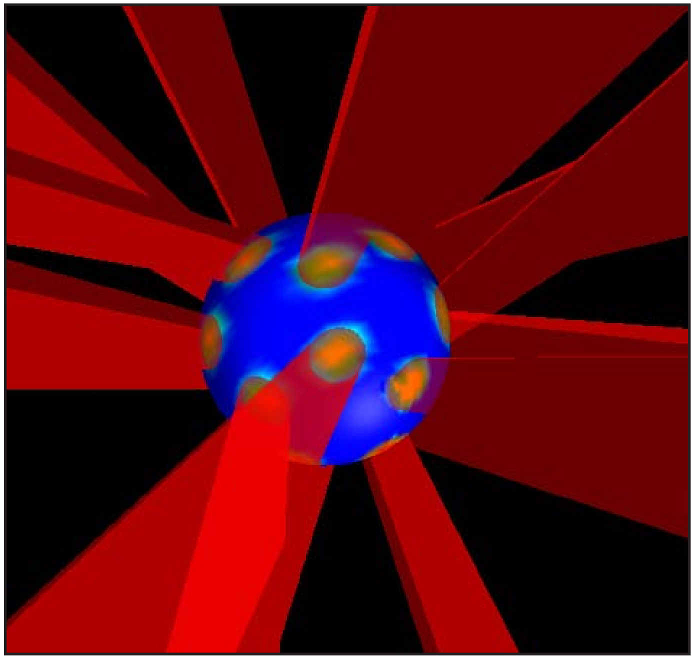
- Design viable implosion platforms over a variety of facilities
- Develop a wide database evaluating strengths and faults of shock-ignition (SI) designs
- Design experimental platforms for OMEGA and the NIF

LPI

- Identify, quantify, and mitigate preheat during the fuel-assembly phase
- Determine the benefits and detriments of spike-pulse preheat
  - enhanced drive
  - fuel-assembly preheat
  - backscatter losses

Contributors

K. S. 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…



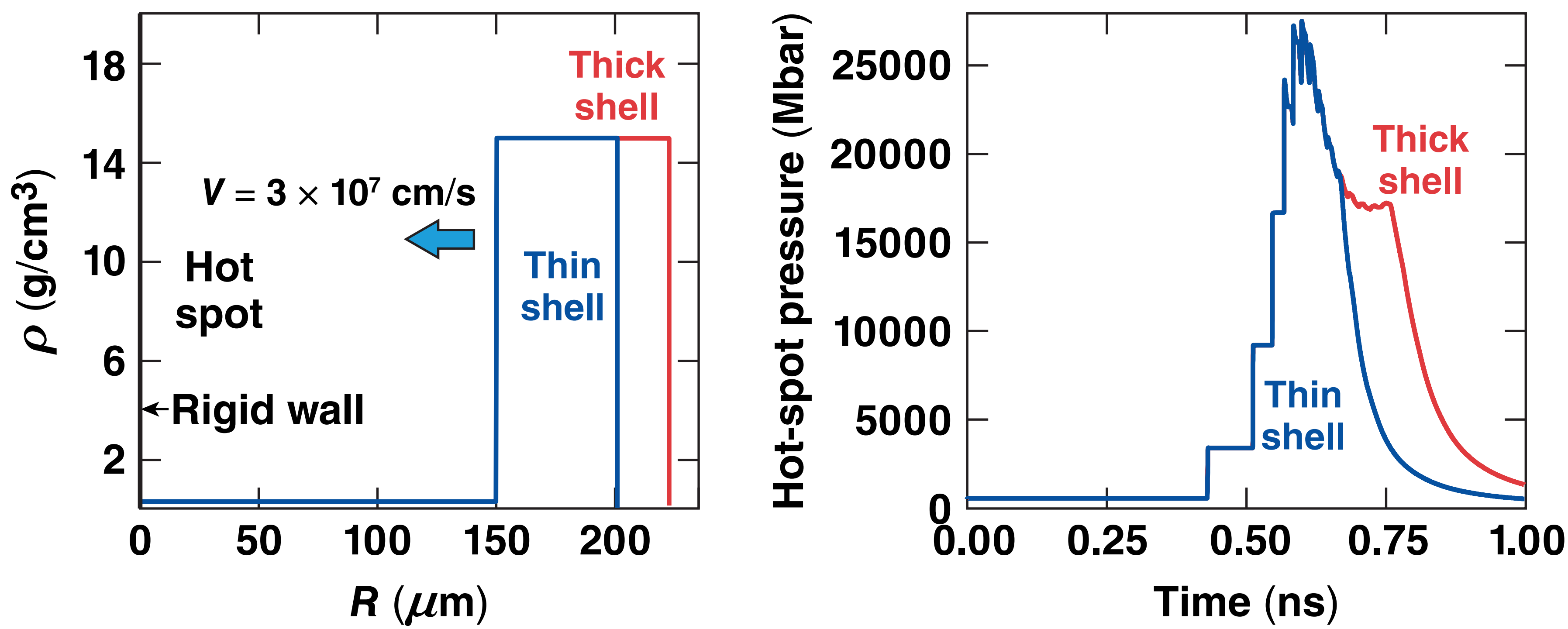
The puzzle of high gains: how to ignite low-velocity imploding targets

- 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 not 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?

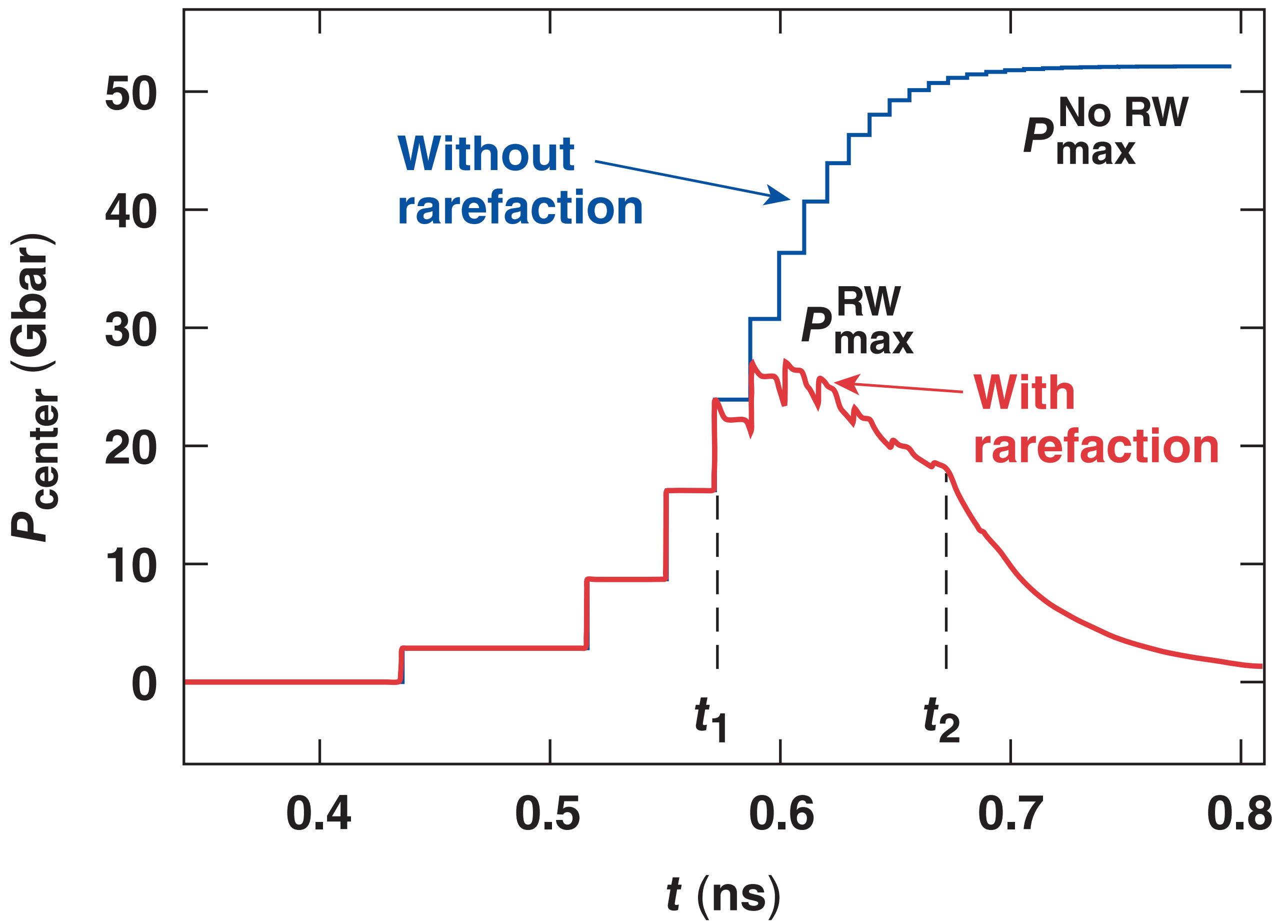
Raising the kinetic energy by thickening the shell does not increase the hot-spot pressure

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



TC8240

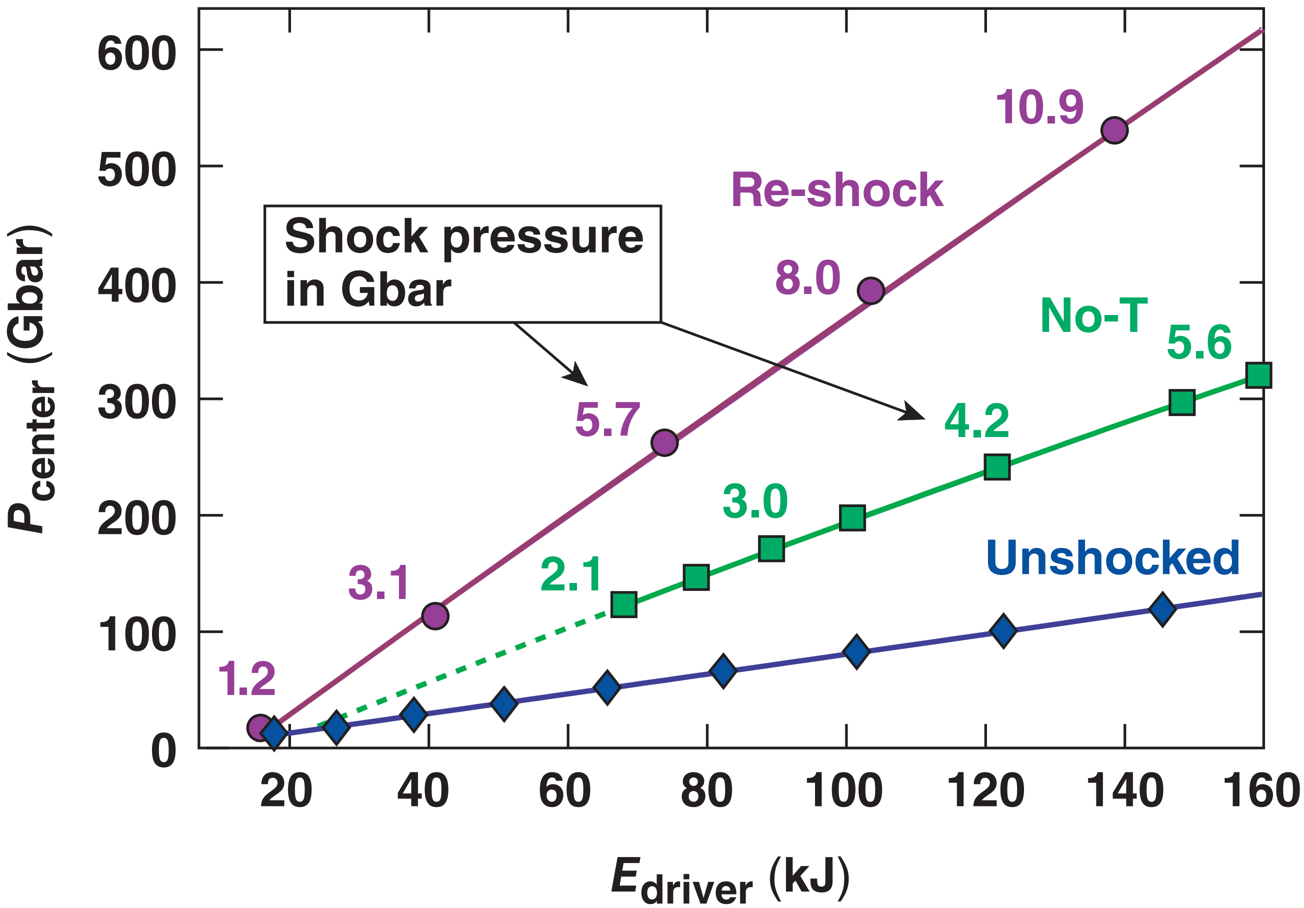
Without rarefaction waves, the peak hot-spot pressure would be twice as high



TC9190

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

The re-shock technique produces the highest hot-spot pressure



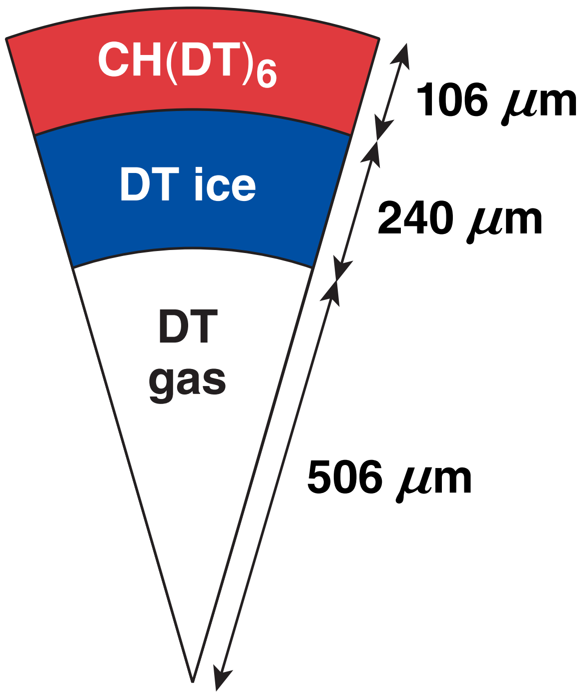
The shock pressure is high because of the planar geometry

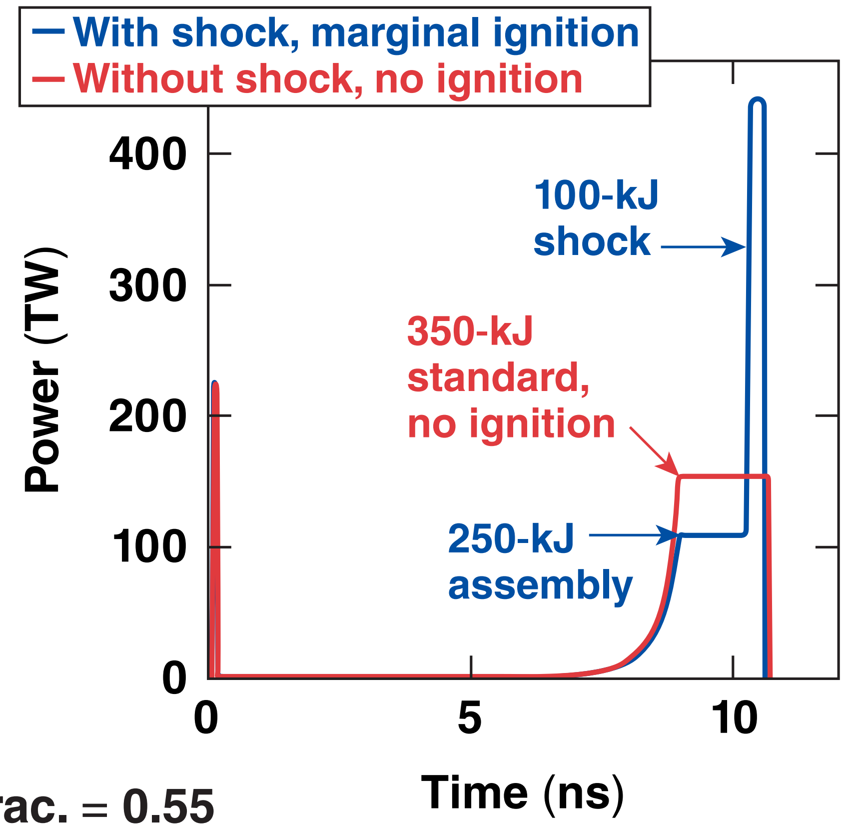
TC9201

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

Optimal shock-ignition targets are wetted-foam shells (in the absence of hot-electron preheat)

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

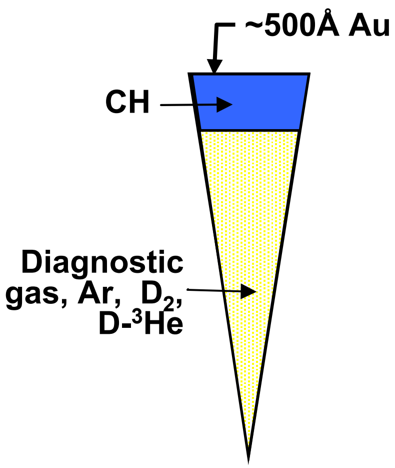


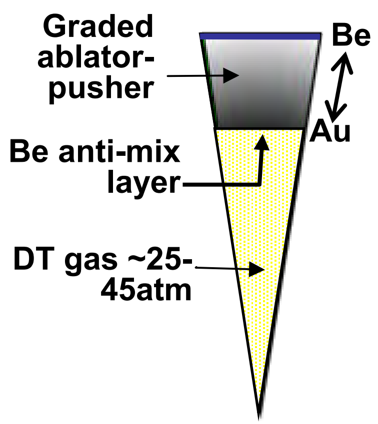


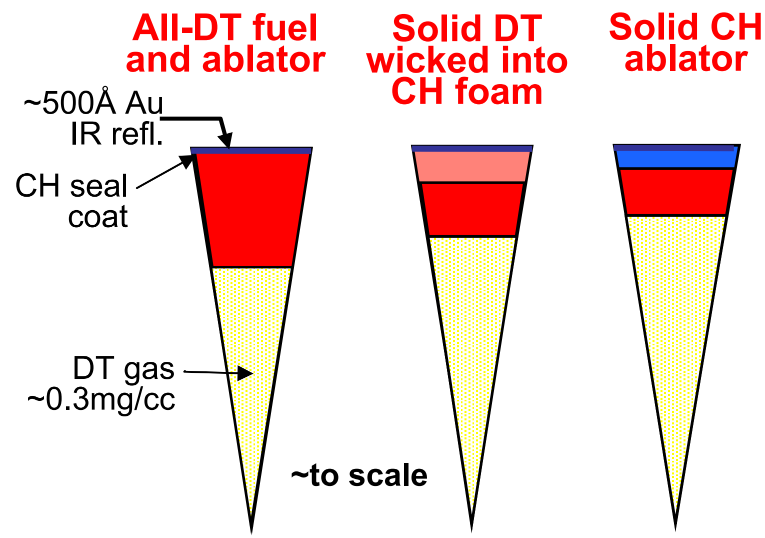
- Standard pulse-shape abs. frac. = 0.55
- Shock-ignition pulse-shape abs. frac. = 0.50

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

Candidate NIF shock ignition targets

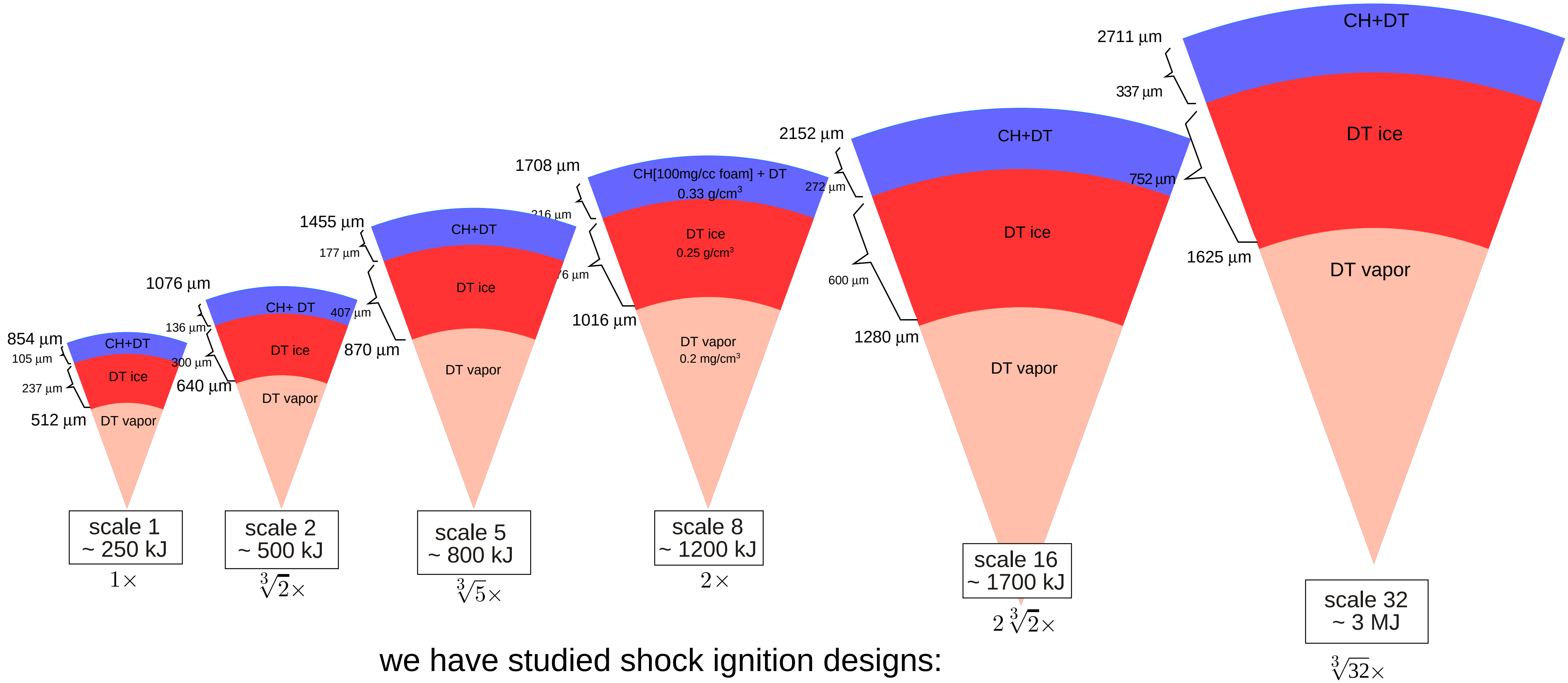






Non-Cryo Hydro-Equiv. CH	Non-Cryo Pushered Single Shell	High Gain Cryo	
• Immediate term (~1-3yr) tests of polar drive symmetry, shock coupling, late-time LPI with day-1 hardware • Diagnostic yields only at ~0.5MJ drive	• Near term (~3yr) tests of room-temp volumetric ignition at ~4keV • Gain/yield ~1/1MJ @ ~1.5MJ drive • Req'd NIF hardware?	• Medium term (~4+yr) tests of high gain shock ignition @ <1MJ • Gain/yield ~60/30MJ @ 0.5MJ drive • Req'd NIF hardware?	• Longer term (≥6yr) tests of high yield shock ignition • Gain/yield ≥100/100MJ @ ≥1MJ drive

Overview: shock ignition targets designed for high gain with KrF



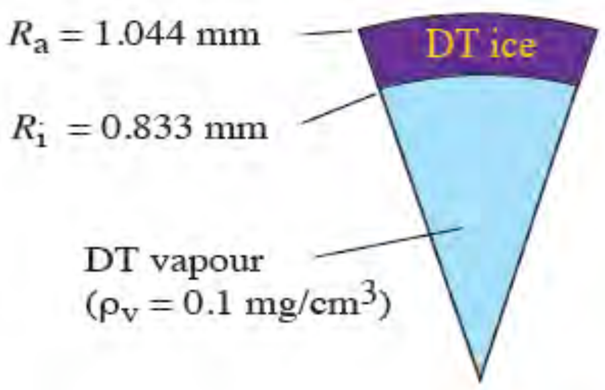
we have studied shock ignition designs:

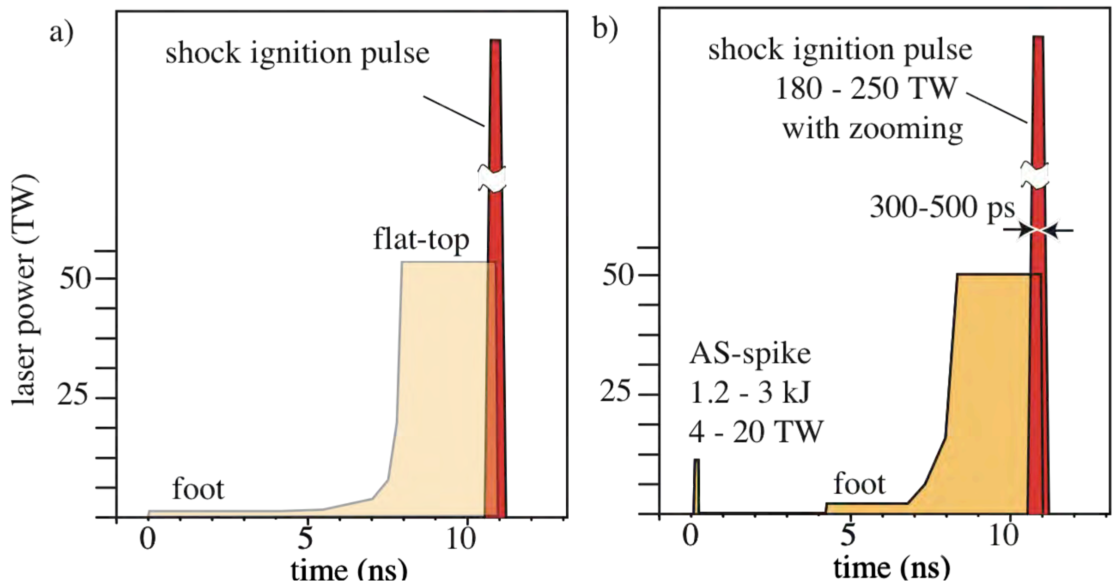
- low-aspect (AR=2.5) foam/DT targets
- driven by 248 nm KrF light
- laser spot size is zoomed twice
- target mass varied by a scale factor of 32
  (scale 1 = ~250 kJ - scale 32 = ~3 MJ targets)
- target adiabat is kept moderately low (α~2)

HiPER baseline target -- Shock-ignition

Target: HiPER baseline target

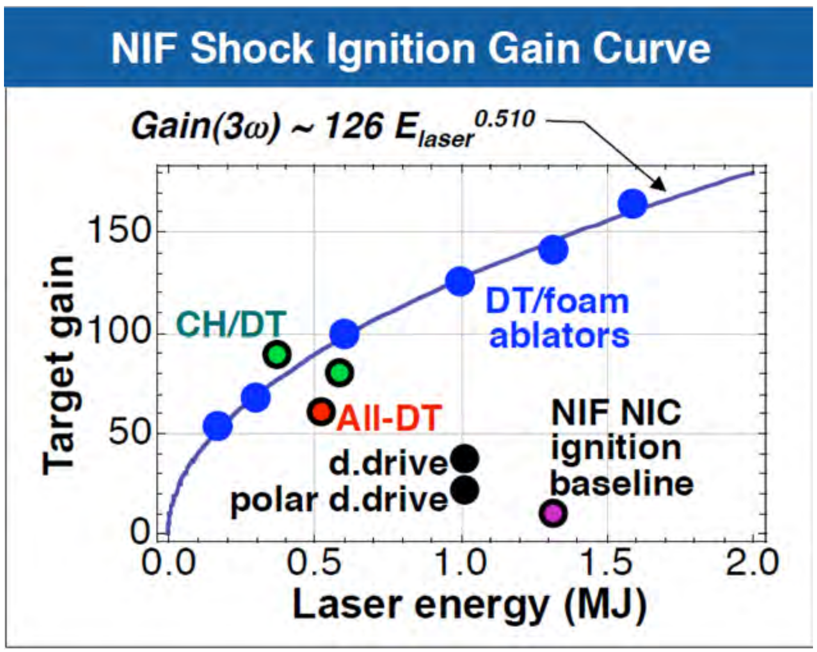
Laser wavelength = 0.35 μm
Compression energy: 180 kJ
Focal spot: 0.64 mm (compression)
0.4 mm (SI)



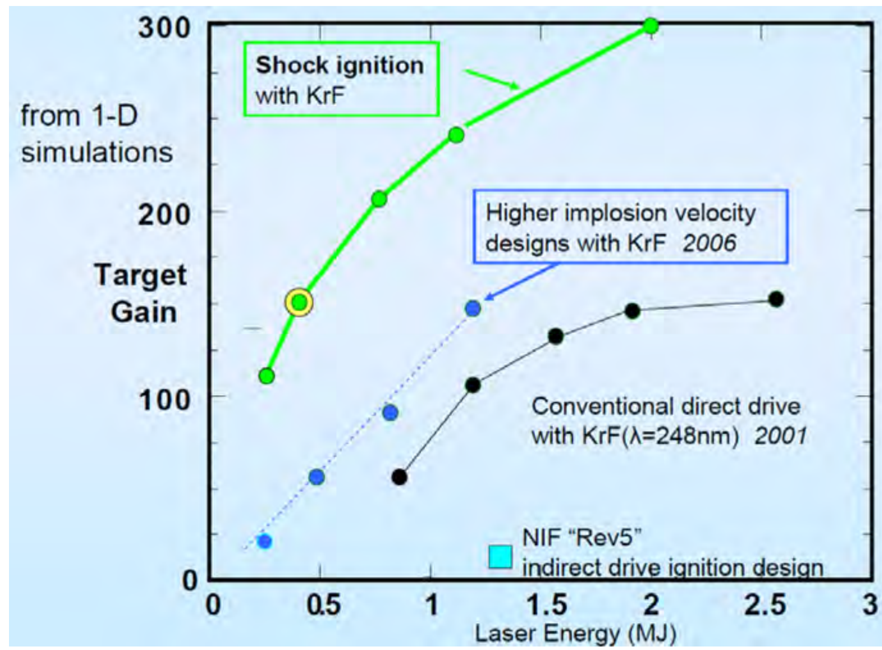


Target: S. Atzeni, A. Schiavi and C. Bellei, PoP, **15**, 14052702 (2007)
Pulses: X. Ribeyre *et al*, PPCF **51,** 015013 (2009);
S. Atzeni, A. Schaivi, A. Marocchino, PPCF (2011)

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



L. J. Perkins (LLNL)



A. Schmitt (NRL)

Shock ignition: pros & issues

PROS

- Implosion velocity smaller than for central ignition
  - ⇒Lower intensity, smaller RTI growth => more room for direct-drive
  - ⇒Potentially higher gain
- Ignition configuration: Non isobaric => higher gain (than central ignition)
- Spherical targets

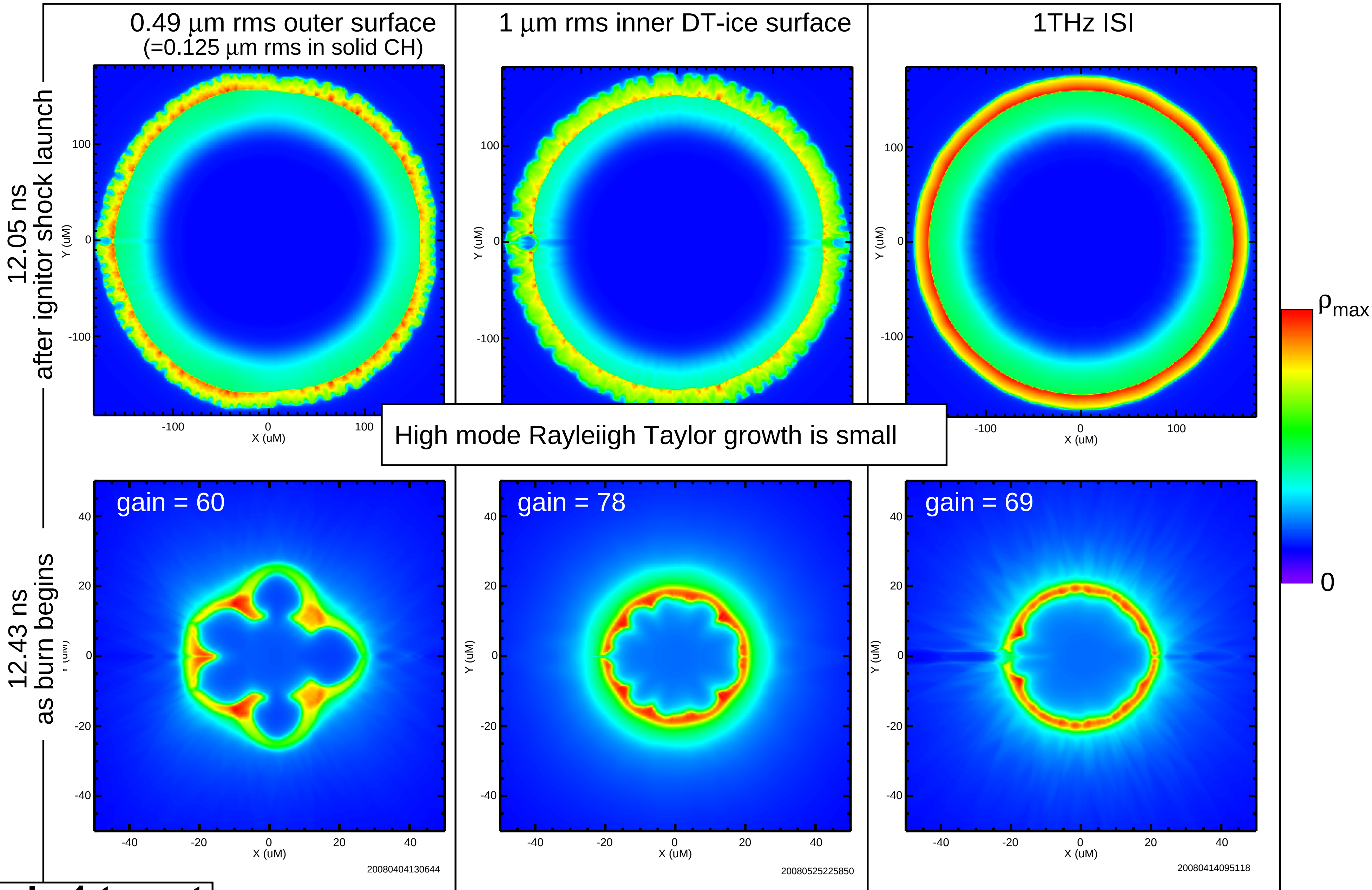
ISSUES, DESERVING EXPERIMENTS (@ NIF, Omega?)

- Laser-plasma interaction at 10^{16} W/cm^2: backscattering? Hot electrons?
- Energy transport at above intensity
- Shock propagation through perturbed materials

MEANWHILE: WHAT ABOUT ROBUSTNESS?

2D High-resolution simulation (ℓ=1-256)

Three different sources have been simulated: outer and inner surface perturbations and laser imprint.

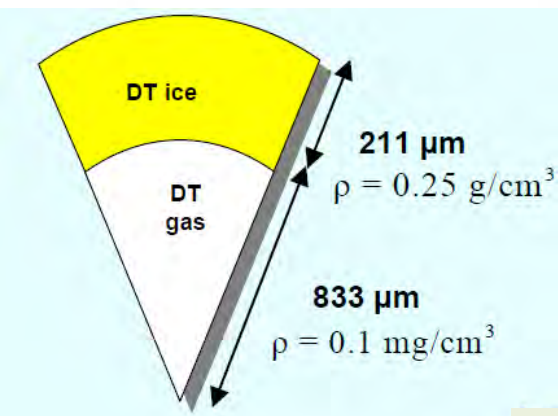


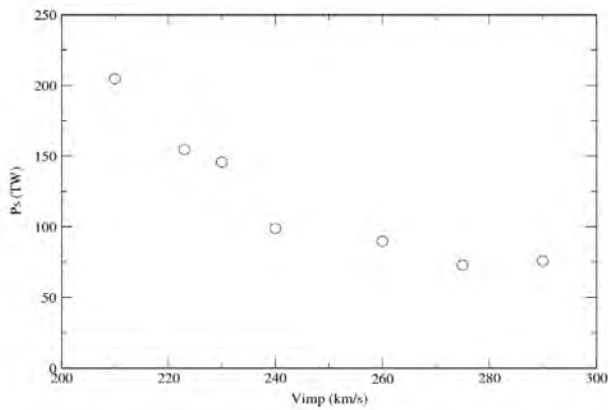
scale 1 target

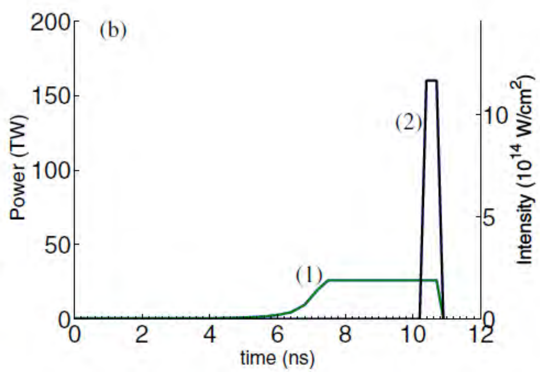
The spike power and launching time are optimized for HiPER shock ignition targets

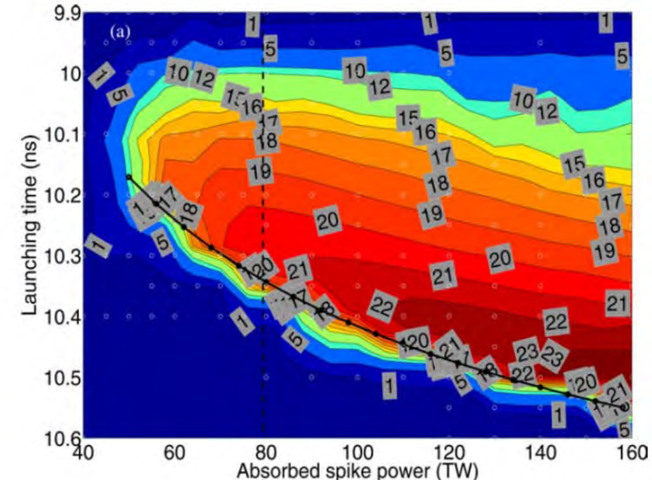
HiPER shock ignition target

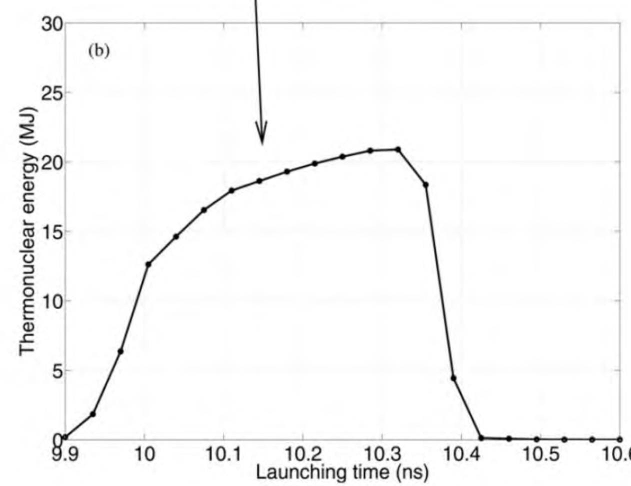
Initial aspect ratio	$\simeq 5$
In-flight aspect ratio	$\simeq 35$
In-flight mass (mg)	$\simeq 0.28$
Implosion velocity (km s^{-1})	$\simeq 290$
Adiabat parameter	$\simeq 1.0$
Peak density (g cm^{-3})	$\simeq 625$
Peak areal density (g cm^{-2})	$\simeq 1.50$







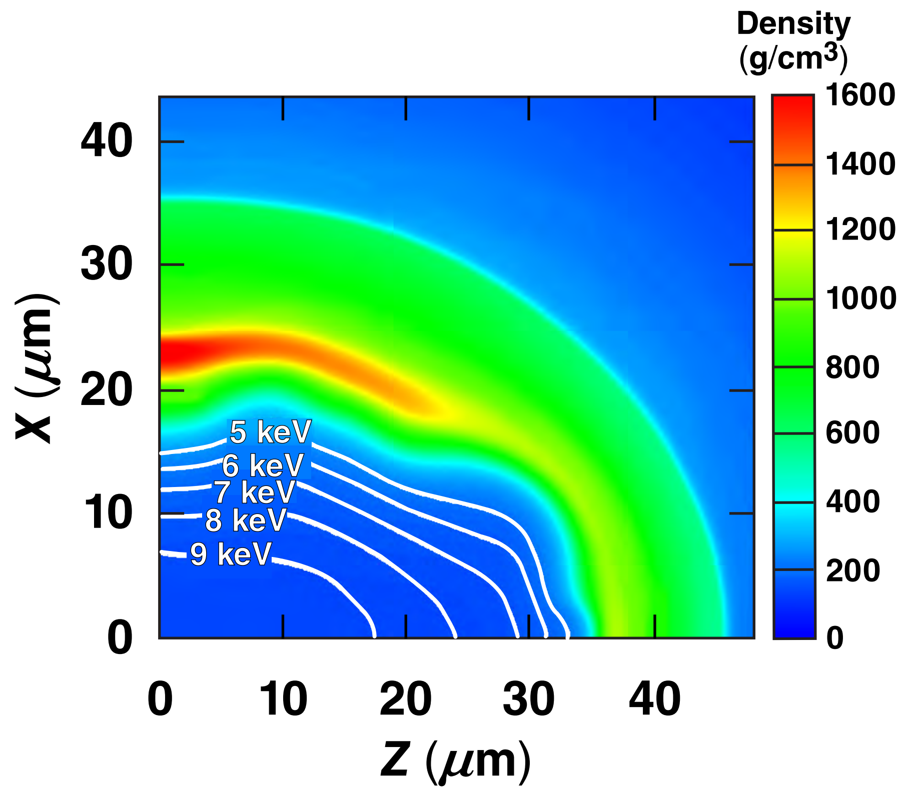




Ribeyre, Schurtz, Lafon, Galera, Weber, PPCF 51, 015013 (2009)

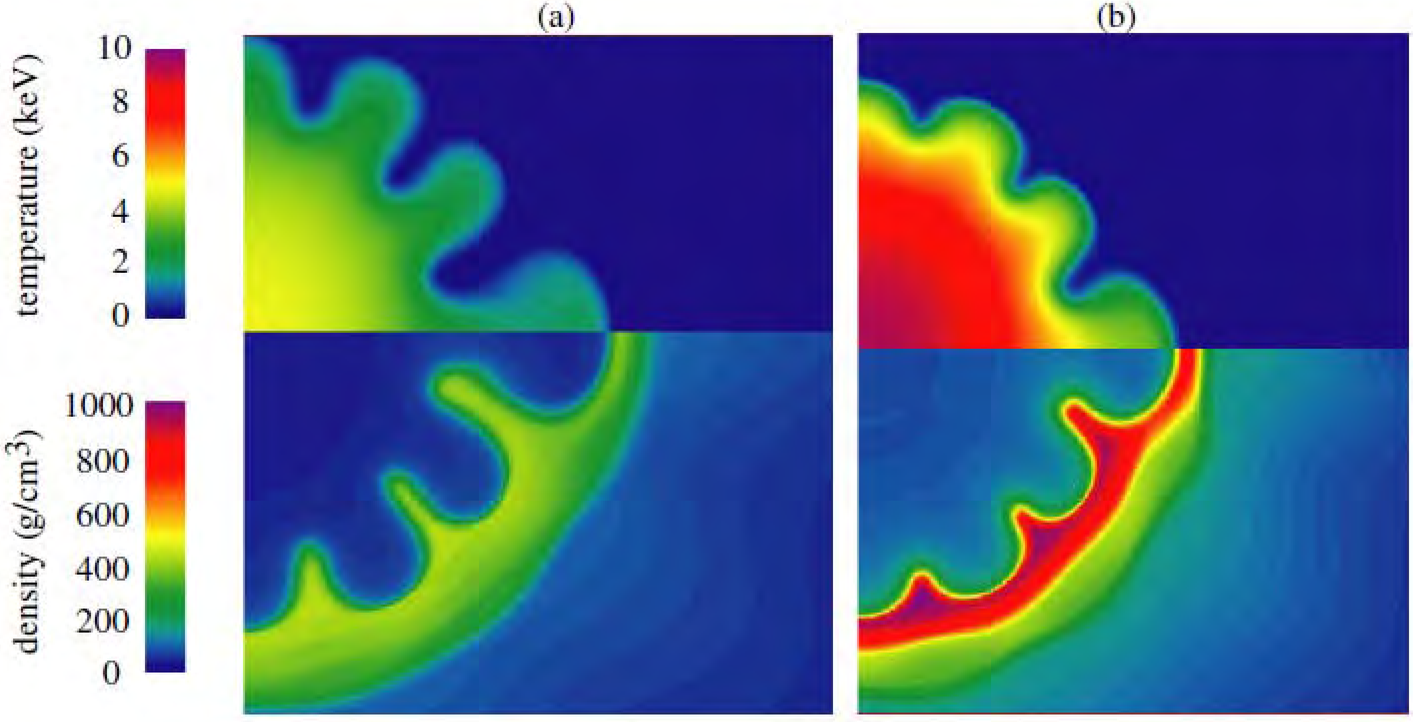
Symmetric 2-D *DRACO* simulations performed with similar targets indicate robustness to ice roughness >3.5-μm rms

- Symmetric laser irradiation
- *DRACO* simulations with 3.5-μm-rms roughness in modes $\ell = 2$ to 50
- Target ignites with full gain
- Upper limit on robustness to ice modes not yet explored
- Other nonuniformity studies to follow (imprint, target offset, polar drive, etc.)



TC9112

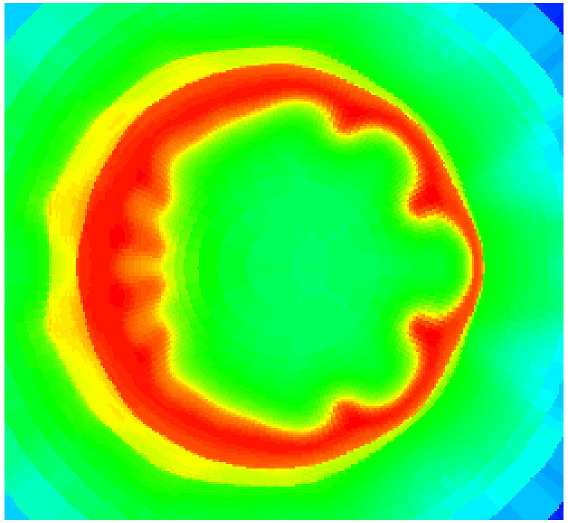
Ignitor-return shock collision seems to reduce the deceleration RTI growth before ignition

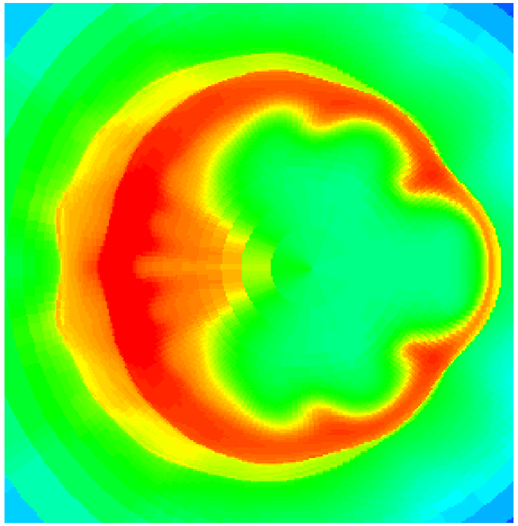


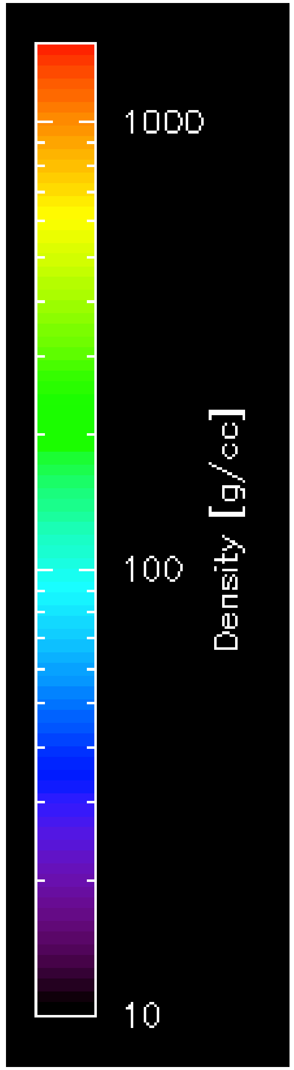
Atzeni, Davies, Hallo, Honrubia, Maire, Olazabal, Feugeas, Ribeyre, Schiavi, Schurtz, Breil, Nicolai, Nucl. Fusion 49, 055008 (2009)

Shock-ignition: sensitive to mispositioning

Density maps when central T_{ion} = 10 keV
(80 * 80 μm)







10 μm displacement

Gain = 95% of 1D gain

20 μm displacement

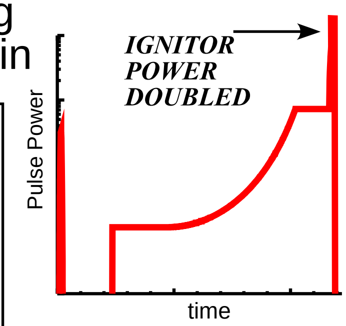
Gain = 1% of 1D gain

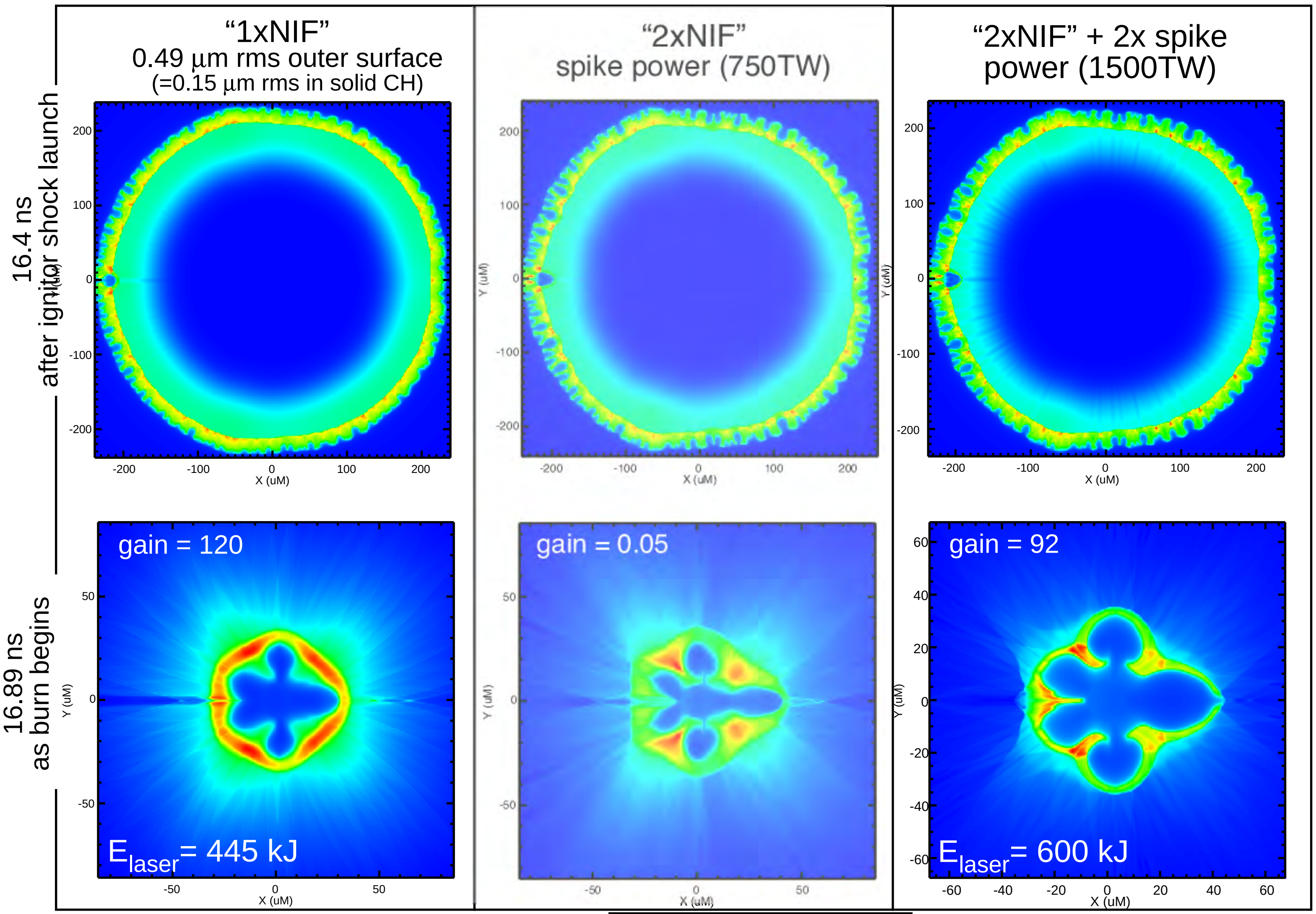
S. Atzeni, A. Schiavi, A. Marocchino, PPCF 2011

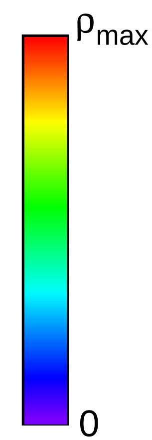
2D High-resolution simulations (ℓ=1-256)

...But increasing the ignitor power restores significant gain

fixed:
doubling the surface roughness ***and*** doubling spike power recovers gain

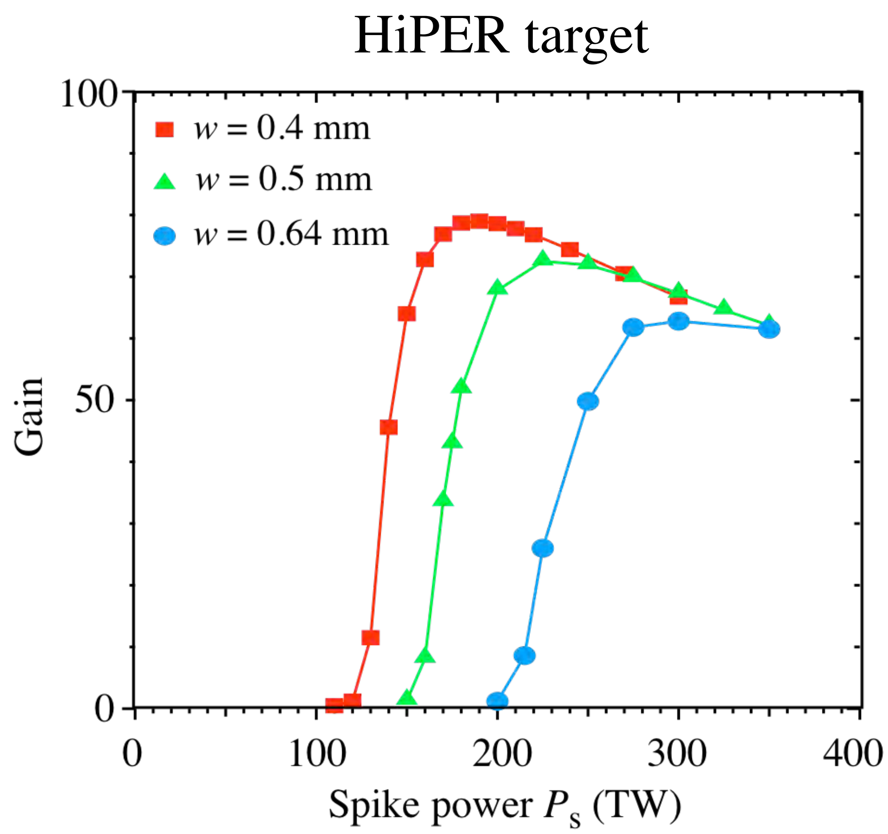






scale 2 target

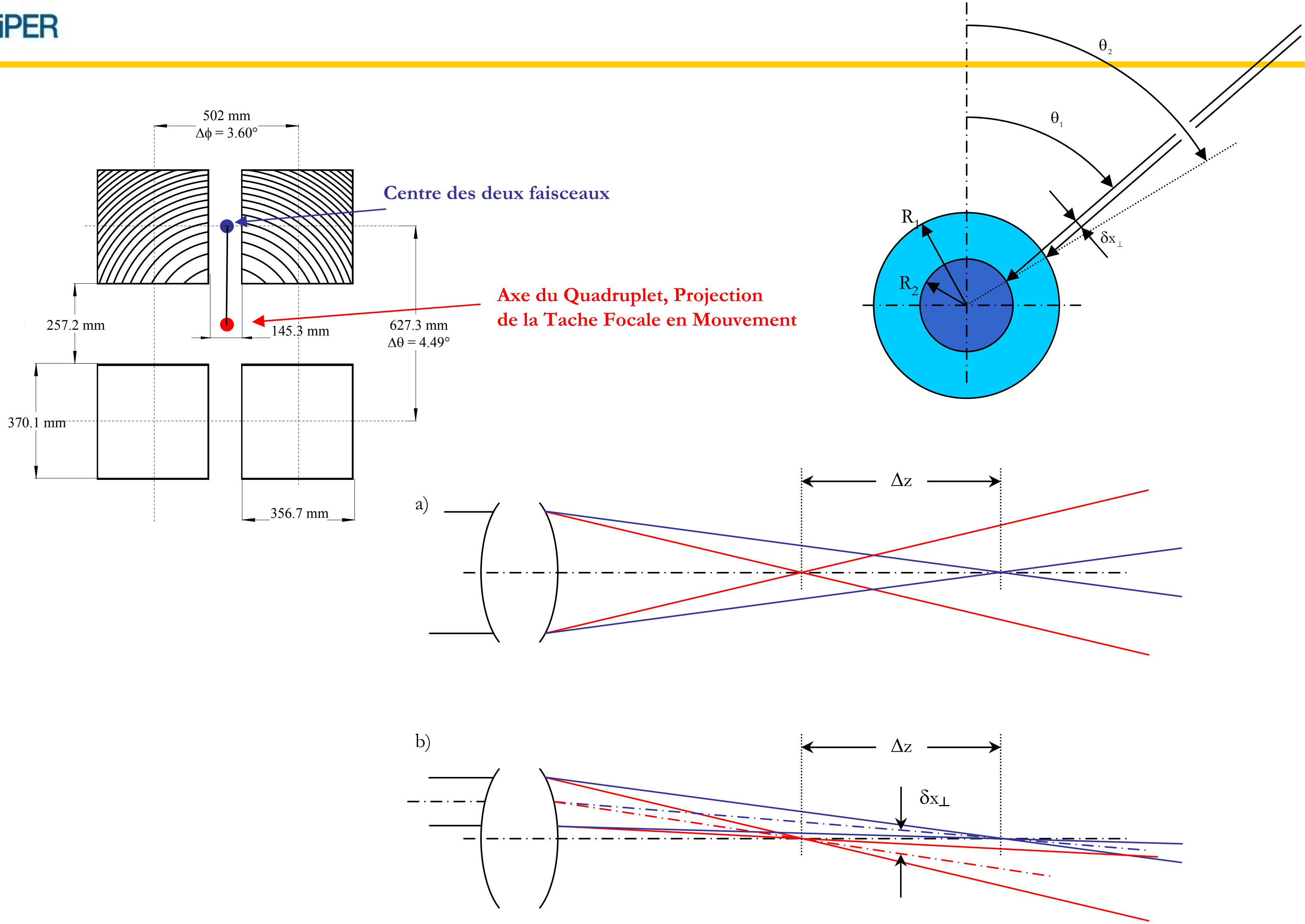
Zooming required to reduce spike power



Gaussian beams, width w_s

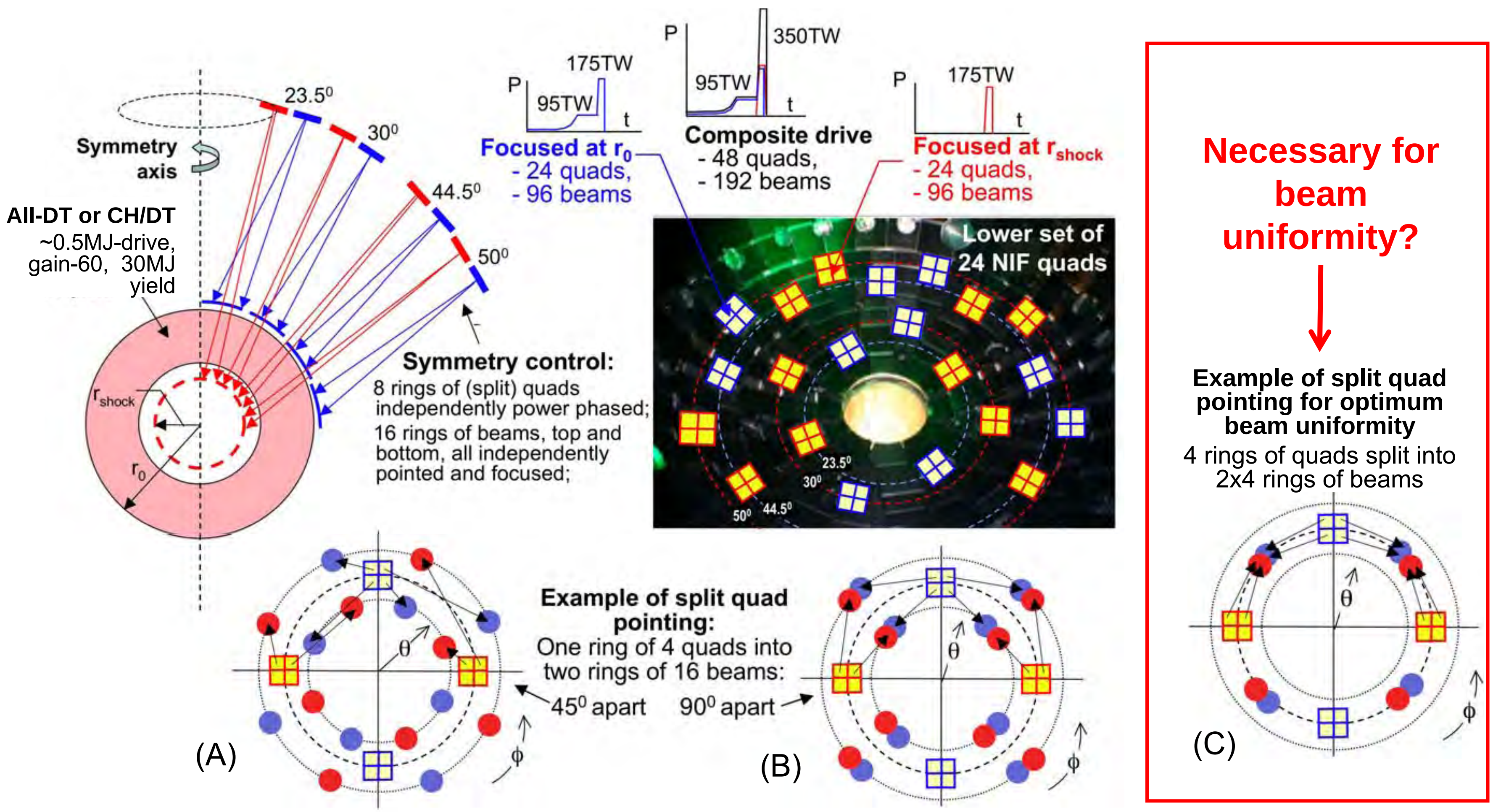
w_s	min. spike power
400 µm	150 TW
500 µm	200 TW
640 µm	270 TW

Dynamic repointing seems achievable on LMJ

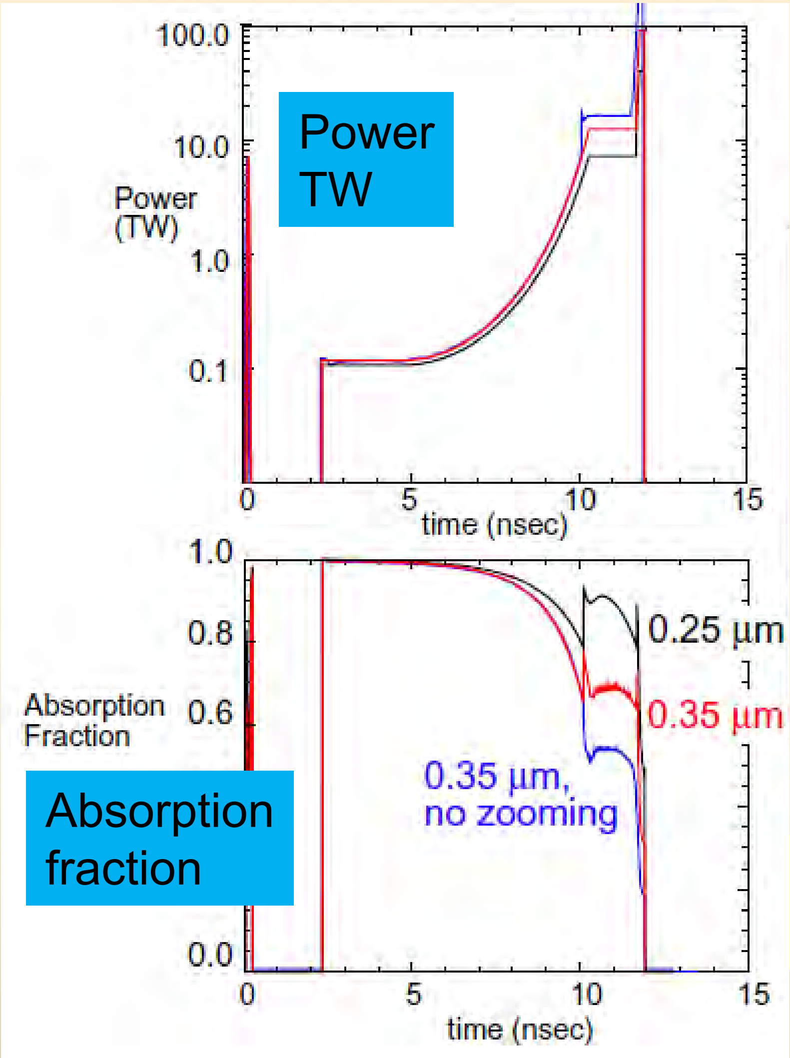


A paramount issue: Optimization of NIF polar drive symmetry and shock coupling efficiency at high convergence ratio

- 96-beams (main+shock) at r_0 at t = 0; 96-beams (shock) zoomed at r_{shock} at t = t_{shock}
- Optimize pointing, focal spots and power phasing on each of 2x4/8 sets of quad/beam rings



Shock ignition benefits from shorter λ and zooming

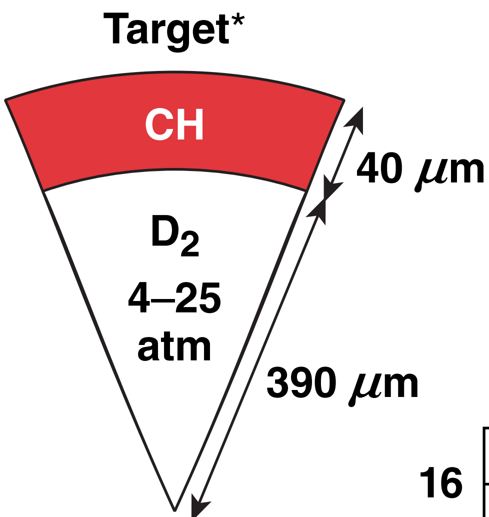


1-D Hydrocode simulations
Fixed low aspect ratio pellet

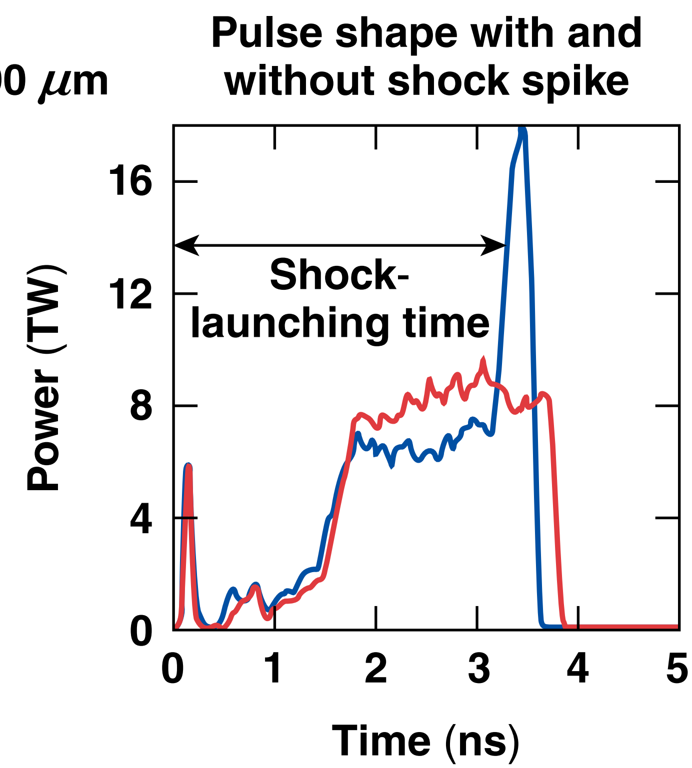
	KrF λ=248 nm with Zoom	Nd:glass λ=351 nm with Zoom	Nd:glass λ=351 nm no Zoom
Laser Energy	**230 kJ**	**430 kJ**	**645 kJ**
Yield	22 MJ	24 MJ	23 MJ
Gain	**97**	**56**	**35**
Peak compression intensity (W/cm^2)	1.55×10^{15}	2.2×10^{15}	
Peak igniter intensity (W/cm^2)	1.6×10^{16}	3.1×10^{16}	

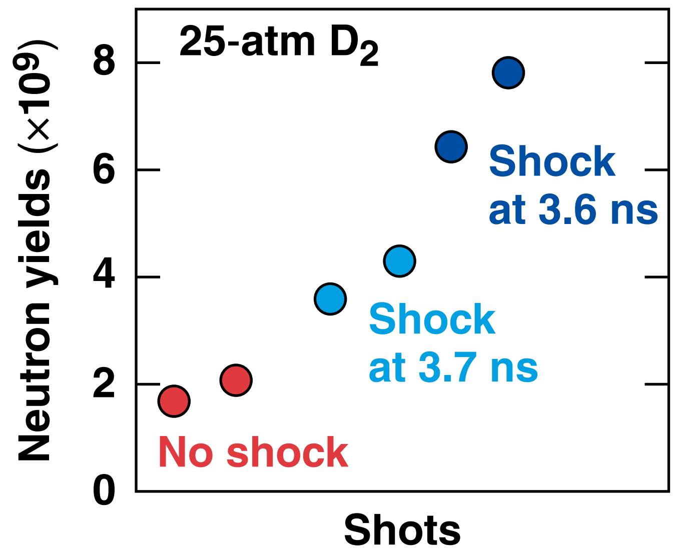
- Significantly higher gain with 248 nm & zoom
- Lower risk from laser plasma instability

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



E_L = 17 to 18 kJ
α = 1.3



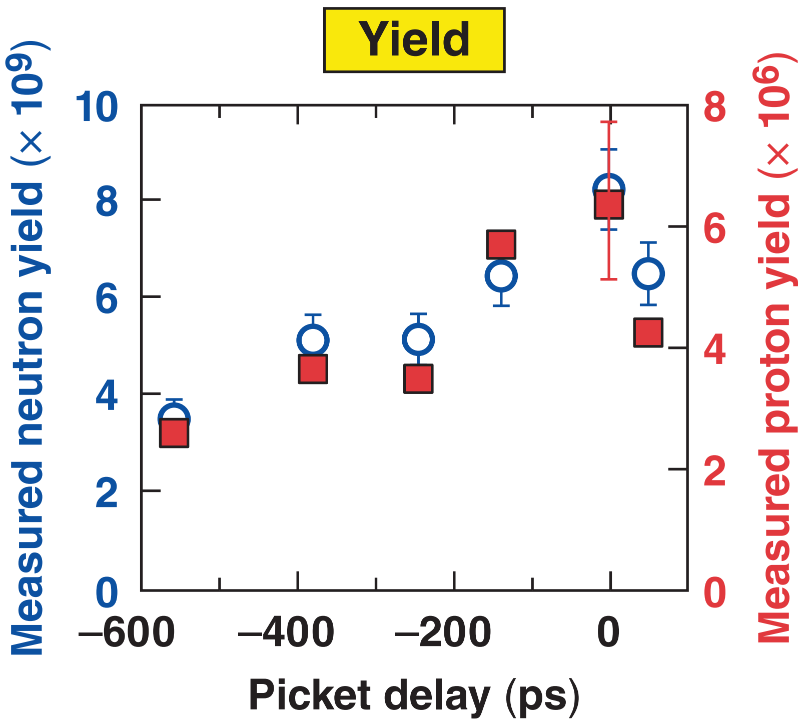


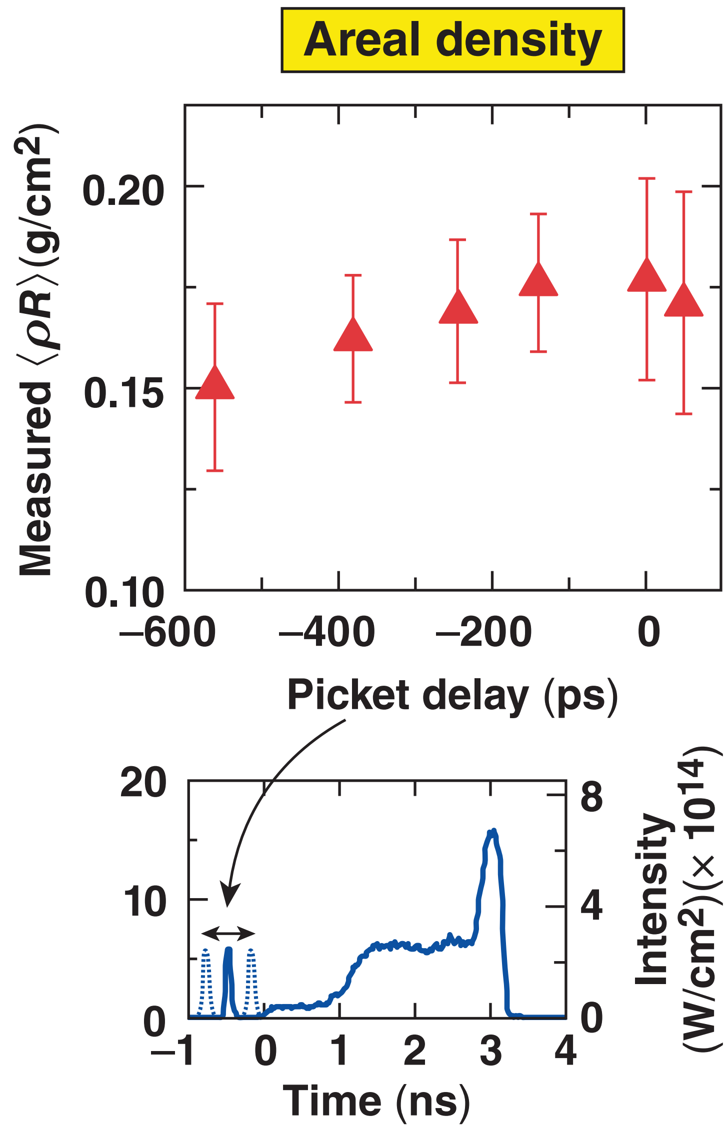
The neutron yield increases considerably when a shock is launched at the end of the pulse.

TC7824

*W. Theobald and C. Zhou (UR-LLE)

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



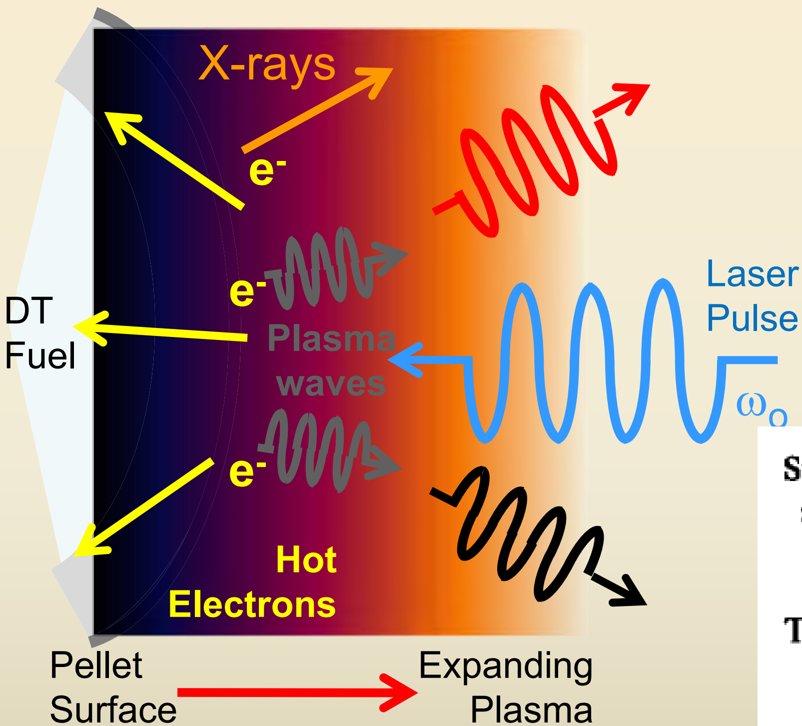


25-atm D_2, E_L ~ 17 kJ,
spike at 2.8 ns

E16131

Laser Plasma Instability limits the maximum intensity

- Can produce high energy electrons that preheat DT fuel
- Can scatters laser beam, reducing drive efficiency



Shorter λ suppresses LPI

$$(V_{osc}/v_{the})^2 \sim I\lambda^2$$

$N_c/4$ instability thresholds
(single planar beam)

Stimulated Raman scatter ($n \approx 1/4\ n_{cr}$)	$I_t \approx \frac{5\times 10^{16}}{L_n^{4/3}(\mu m)\lambda_0^{2/3}(\mu m)} \frac{W}{cm^2}$
Two plasmon decay	$I_t \approx \frac{5\times 10^{15}}{L_n(\mu m)\lambda_0(\mu)} \theta_{keV} \frac{W}{cm^2}$

LPI during the compression pulse?

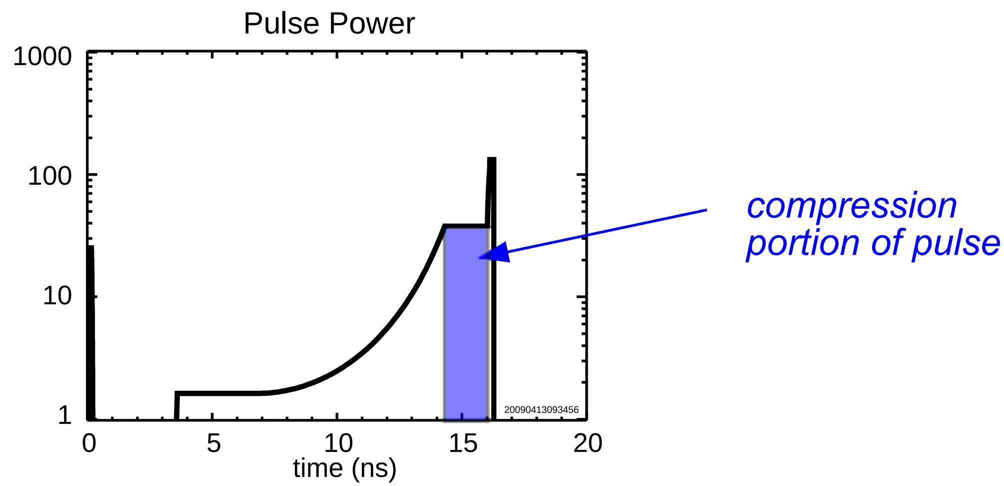
Fast electrons can preheat the fuel and prevent compression.

Instabilities at the quarter critical surface often have the lowest intensity threshold. E.g., the two plasmon ($2\omega_{pe}$) decay threshold is*:

$$I_{15} \sim 80 \, \frac{T_{kev}}{\lambda_{\mu m} \, L_{d,\mu m}}$$

This simple formula has (so far) been **unreasonably effective** in predicting the intensity threshold of the occurrence of instability at $n_c/4$ in a variety of experiments.

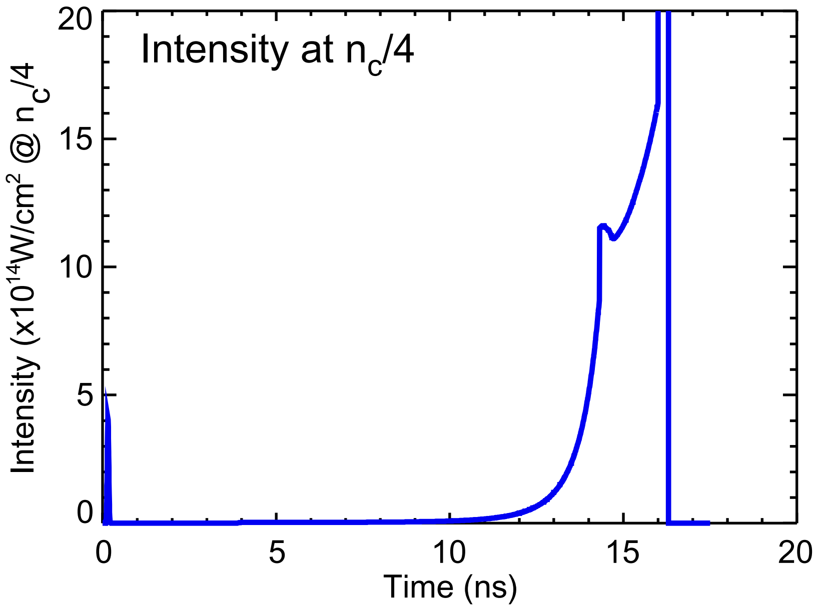
The impact of LPI will depend upon the number and energy of hot electrons generated, which is still quite unknown.

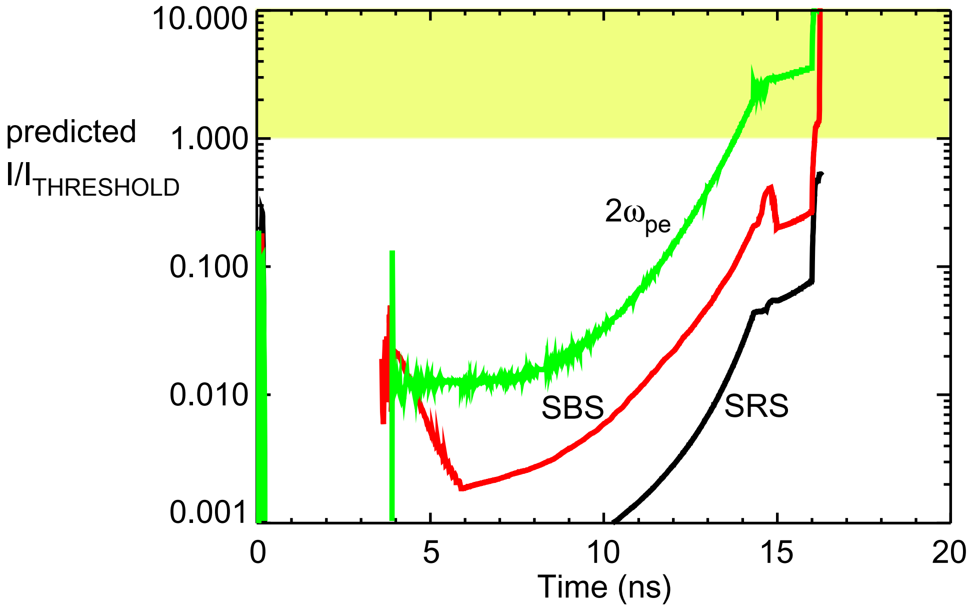


A. Simon, R. Short, E.A. Williams, and T. DeWandre, Phys. Fluids ***26****, 3107 (1983);*
B. Afeyan and E.A. Williams, Phys. Plasmas ***4****, 3788, 3803, 3827, & 3845 (1997).*

The baseline shock ignition target is above the predicted $2\omega_{pe}$ threshold during compression

baseline ~ 500 kJ shock ignition target



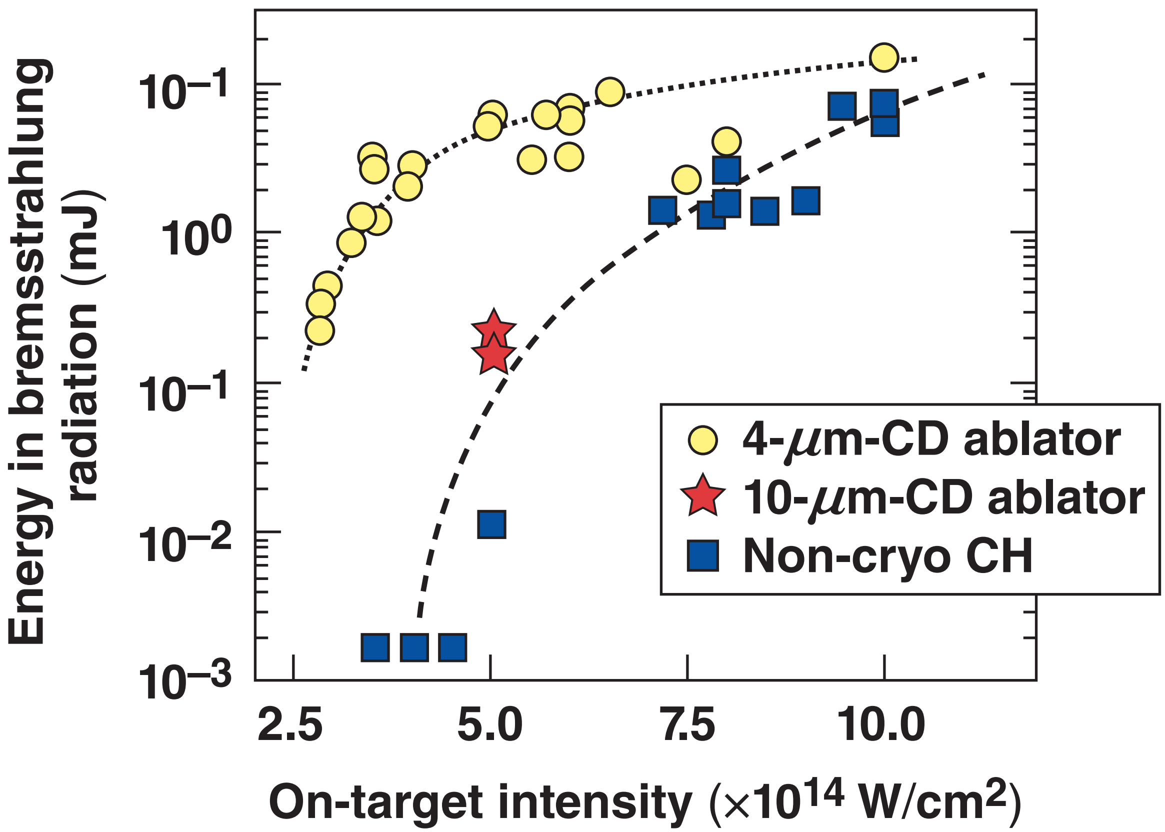


predicted $I/I_{2\omega pe\text{-}threshold}$

$$I_{15} \sim 80 \frac{T_{kev}}{\lambda_{\mu m} L_{d,\mu m}}$$

based on plane EM wave linear
plasma ramp analysis

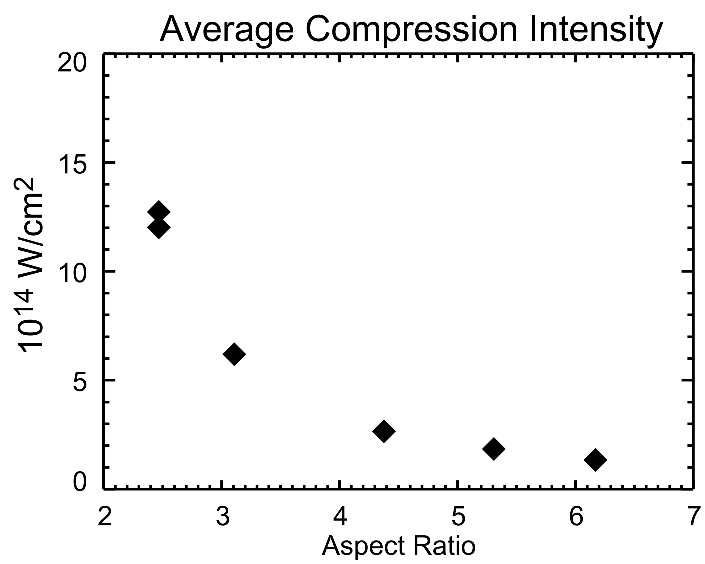
OMEGA experiments show high hot-electron signals for hydrogenic ablators

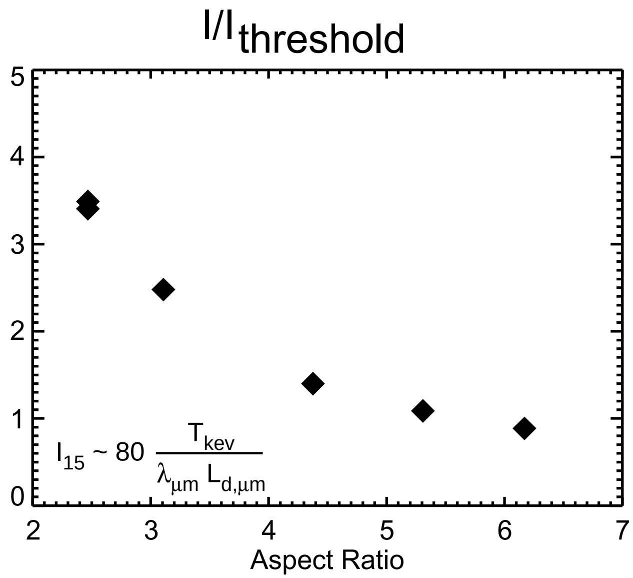


TC9309

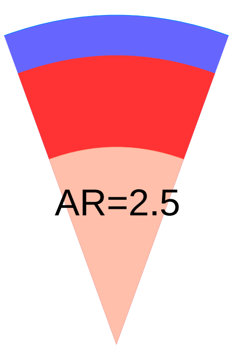
T. C. Sangster *et al*., Phys. Rev. Lett. 100, 185006 (2008).

Increasing the initial Aspect Ratio (AR) allows one to use lower drive intensities and decrease LPI risk

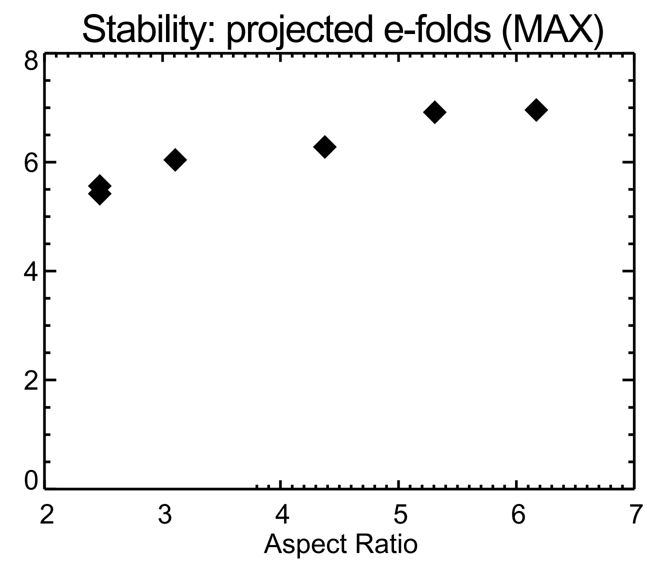


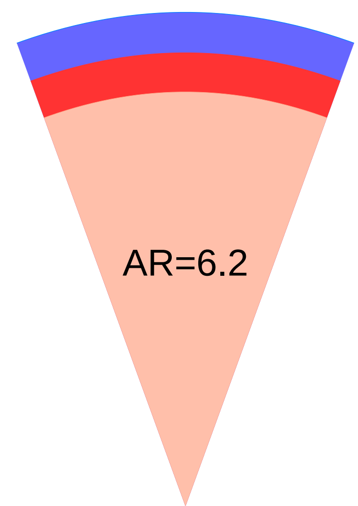


$$AR = \frac{R_{outer} - R_{inner}}{R_{outer}}$$

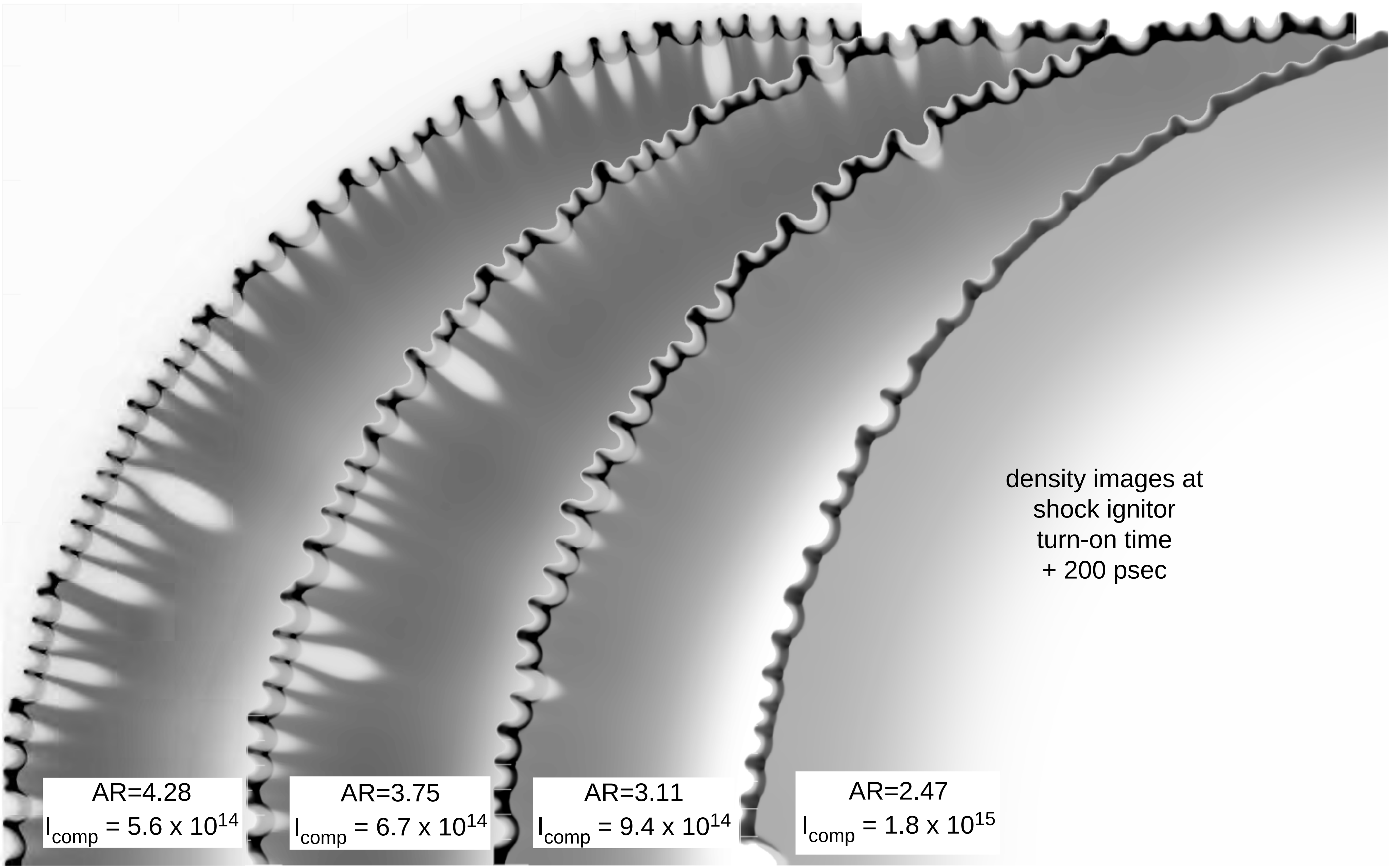


... but stability is worse





Effects of lower intensity: 2D simulations of higher aspect ratio (AR) targets show greater growth of RT



(I_{comp} = maximum intensity during compression pulse)

A New Approach to LPI Control

- Instead of just phase control (in space-time) through masks and electro-optic modulators, or the all purpose PS solution, it is worth exploring the intentional variation of the amplitude and duration of short bursts of laser light ==> **STUD pulses**: Spike Train of Uneven Duration or Delay.

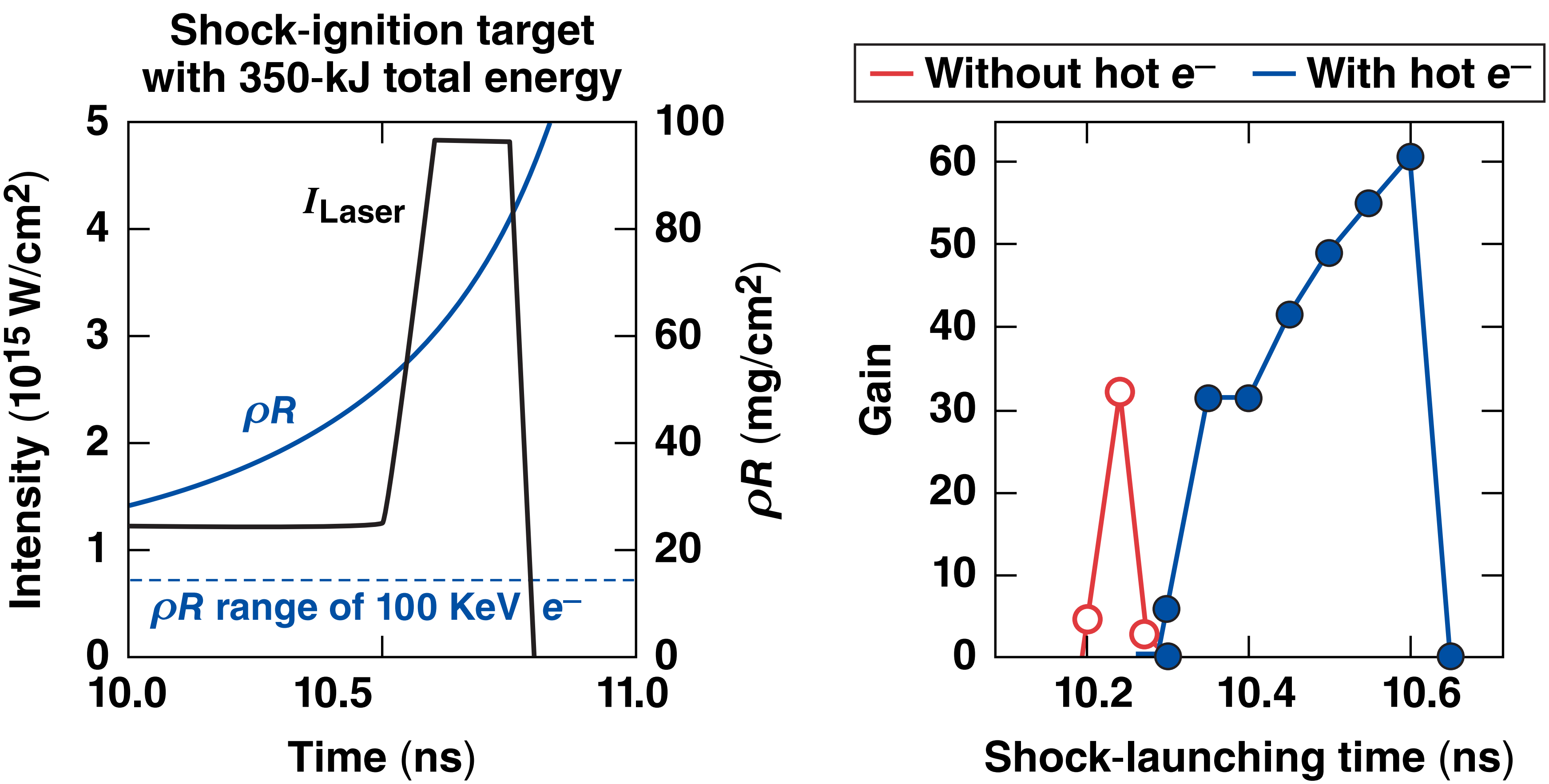
- Use **variable width spikes** to last 4-8 growth times of the most unstable mode to be avoided, and then shut off the pump long enough to disallow self-organization of plasma into coherent large amplitude waves which can then do real damage, and then repeat.

- Divide and conquer the laser's propensity to whip the entire plasma up into a coherent pump driven LPI haven. **Start and stop the interaction processes to avoid cumulative damage**. Three main reasons you win with STUD pulses: Don't allow growth in entire hot spot, avoid hitting the same driven wave by the same or similar hot spot over and over again, damp the wave between recurrence of hot spots to the same location as previously driven waves.

Summary

- We have a good understanding of the linear stage of TPD
- Most hot e^- are produced only in the nonlinear stage of TPD
- Forward hot e^- (>50-keV) flux from plane-wave, 2-D PIC is >10× that of experiment measurements
  - how to account for 3-D effects like speckles?
  - LPI and hydro are difficult to decouple

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

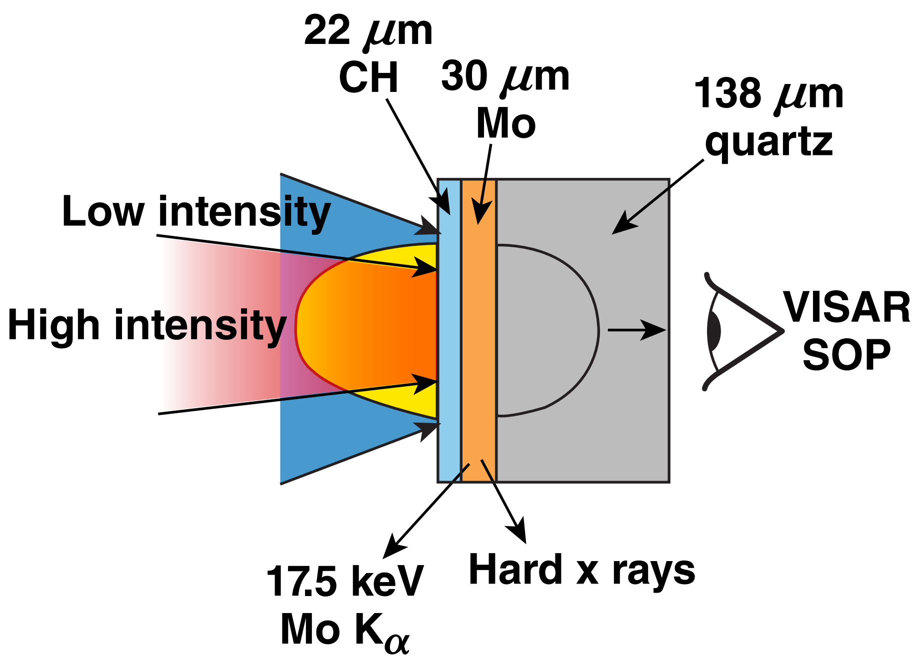


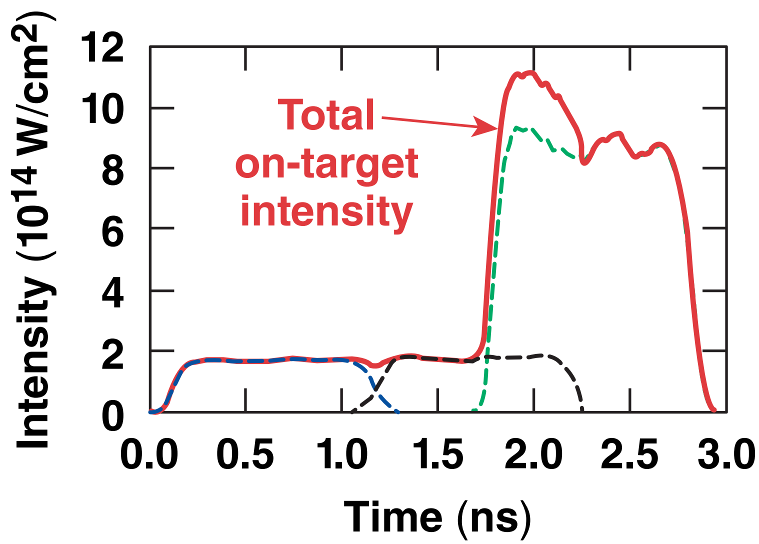
Hot e⁻ with Maxwellian T_{hot} = 150 keV, E_{hot} = 17% of spike energy, treated using a multigroup diffusion model*

*J. Detettrez and E. B. Goldman, LLE, Univ. of Rochester, Rochester, NY, LLE Report No. 36 (1976). Also see K. S. Anderson (this conference).

TC7870

A laser–plasma interaction experiment was performed in planar geometry with overlapping beams



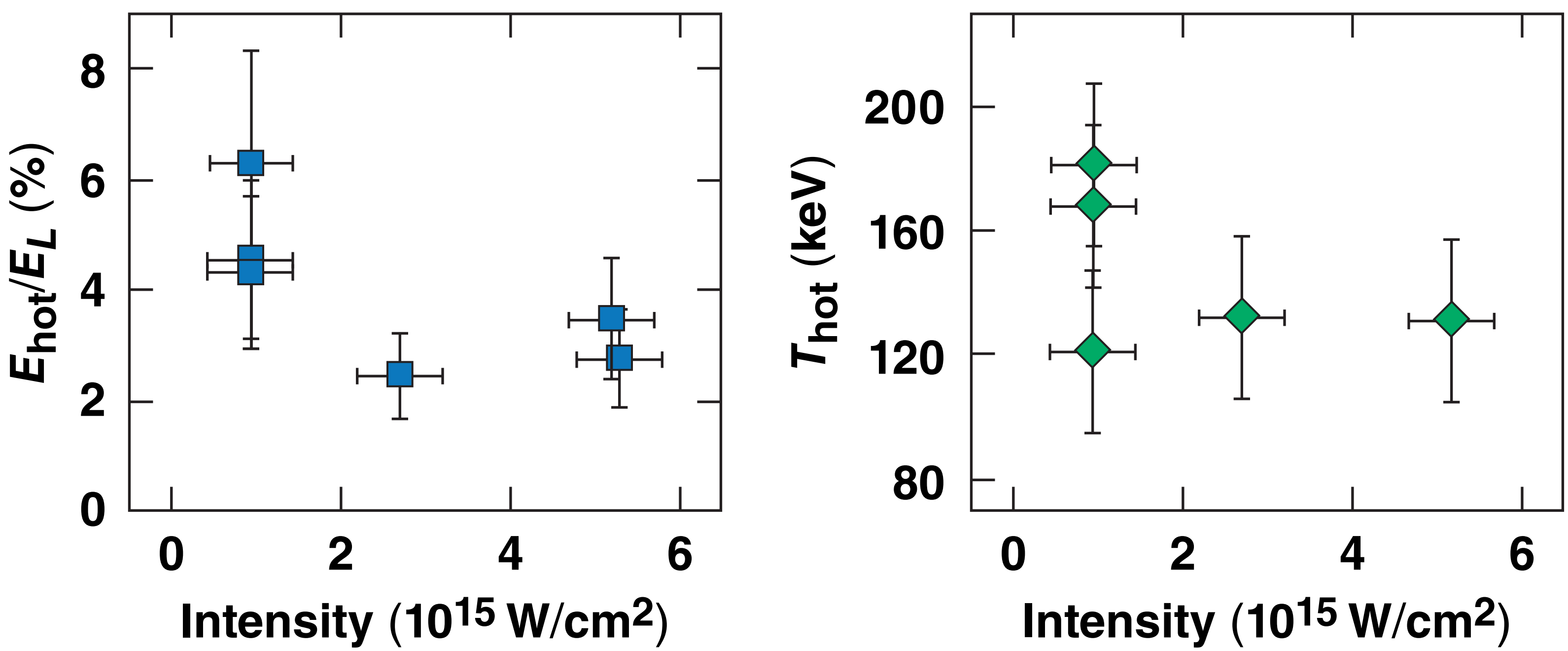


Pre-plasma pulse: ~2×10^{14} W/cm^2
900-μm spot diameter

Shock pulse: ~1 to 5×10^{15} W/cm^2
250- to 600-μm spot diameter

TC9067a

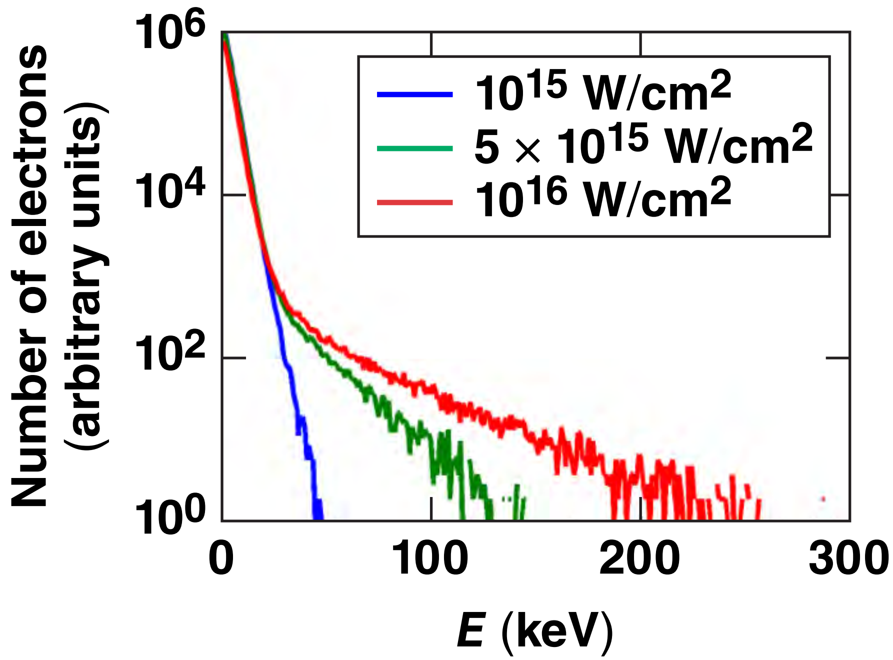
Up to 6% of the high-intensity laser energy is converted into hot electrons

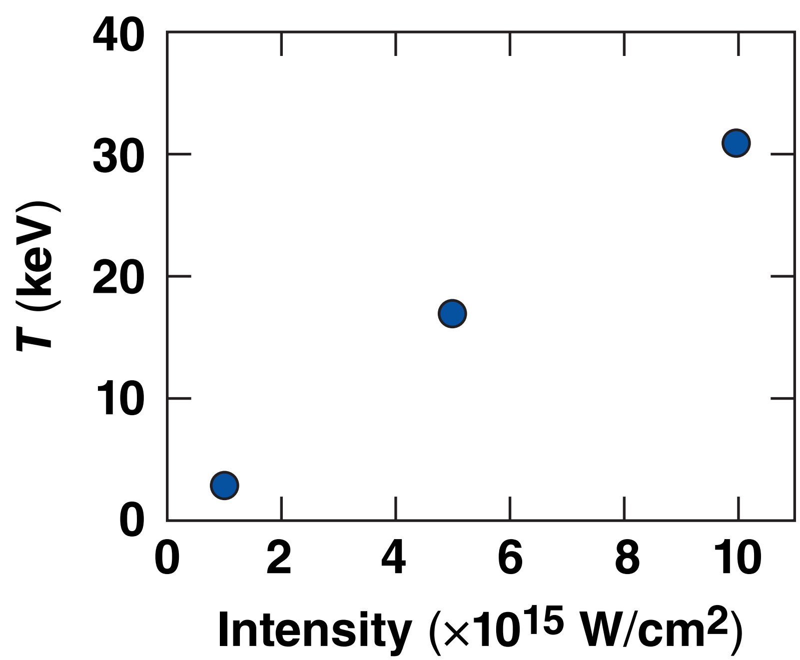


- The measured hot-electron temperature is 3× higher than in spherical geometry
- >150-keV electrons can be detrimental to target performance

TC9069a

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

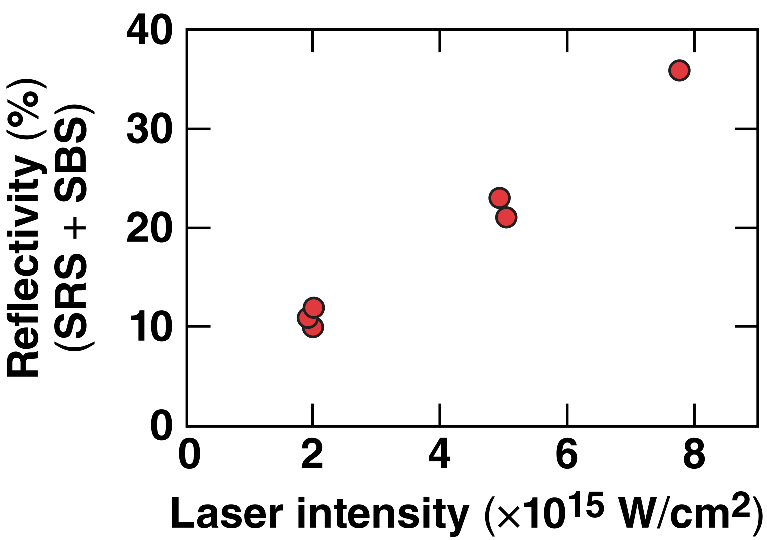




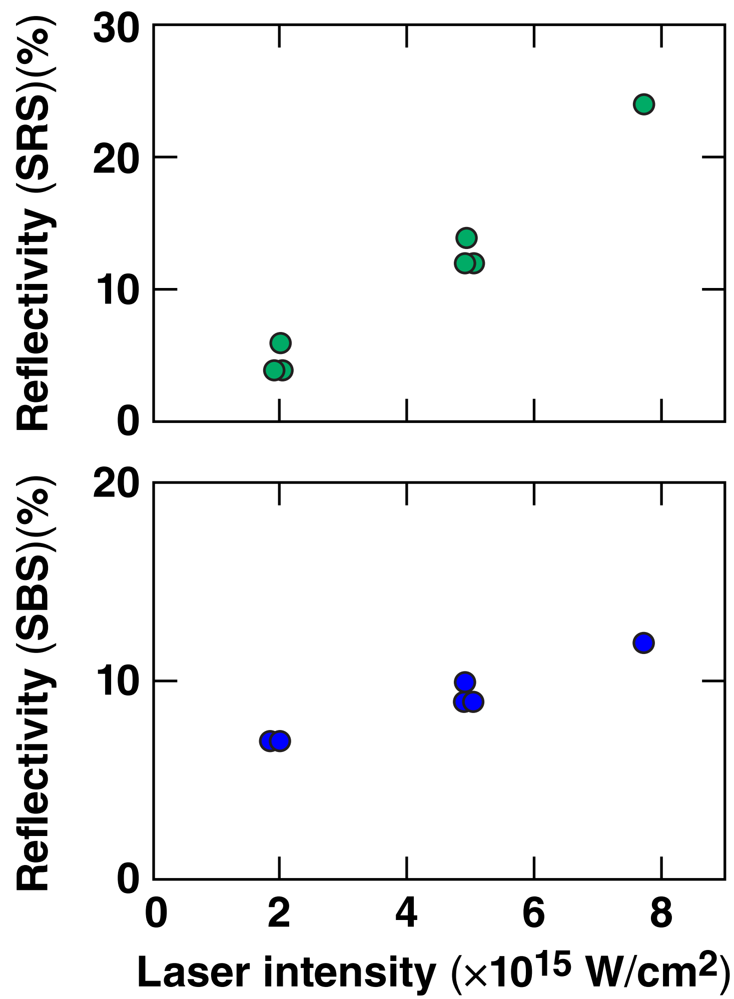
TC9307

O. Klimo *et al*., Plasma Phys. Control. Fusion 52, 055013 (2010).

Up to 35% of the shock-beam laser energy is lost due to backscatter; T_{hot} ~ 45 keV



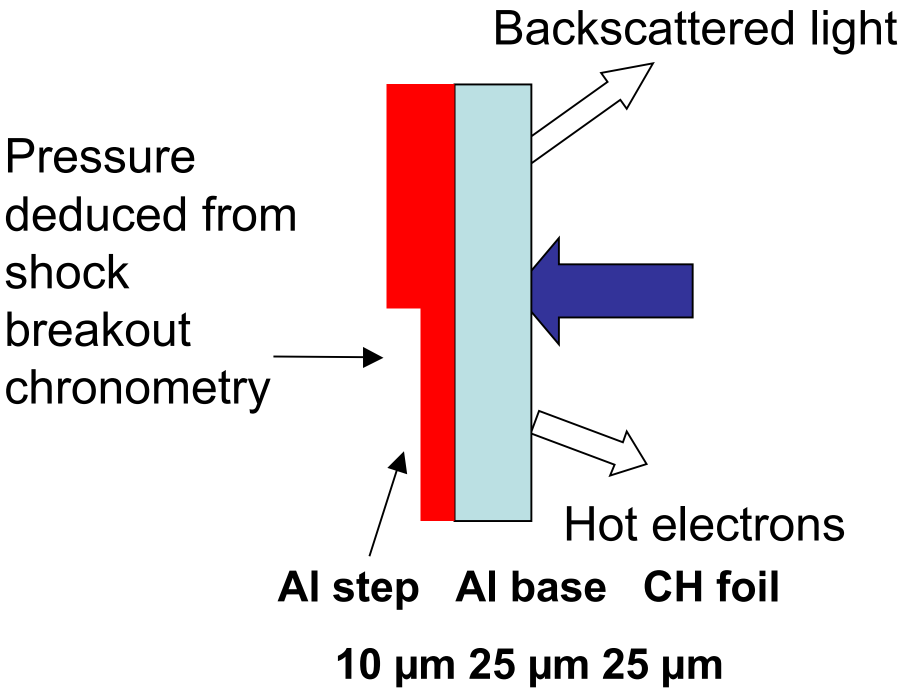
- No measurable signal of the 3/2 harmonic
- SRS dominates back reflection at highest intensity
- SBS reflection is relatively stable at ~10%

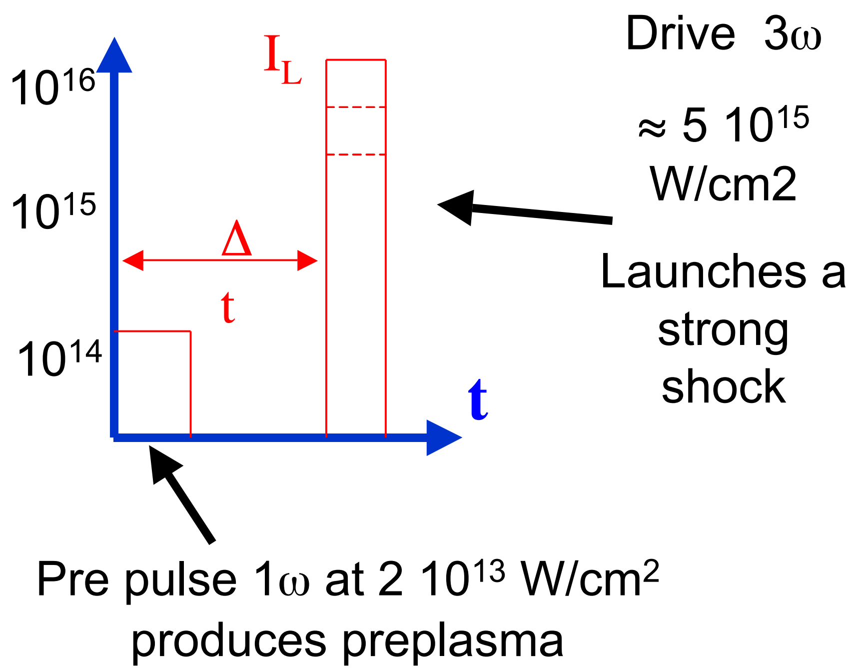


C. Stoeckl *et al*., Bull. Am. Phys. Soc. 54, 265 (2009).
W. Theobald *et al*., Plasma Phys. Control. Fusion 51, 124052 (2009).

E18435b

Sketch of expt. set-up





Prepulse - E = 30 J, λ = 1.3 µm, Φ = 1 mm, τ = 300 ps ⇒ I = 1.2 10^{13} W/cm²

Temperature $$T_e(eV) = 10^{-6}\left(I(W/cm^2)\lambda^2(\mu m)\right)^{2/3} \approx 750\ eV$$

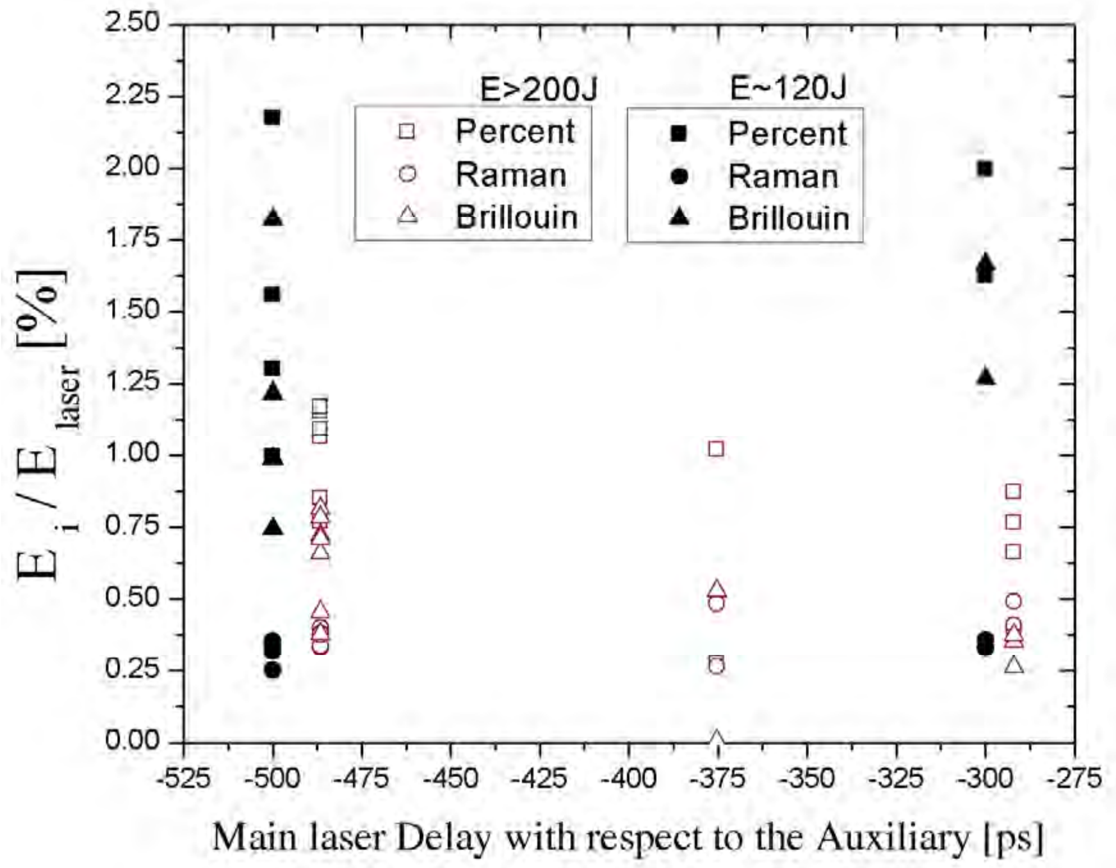
Main Pulse - E = 250 J, λ = 438 nm, Φ =100 µm, τ = 300 ps ⇒ I = 10^{16} W/cm²

Pressure $$P(MBar) = 8.6\left(\frac{I(W/cm^2)}{10^{14}\lambda(\mu m)}\right)^{2/3}\left(\frac{A}{2Z}\right)^{1/3} = 320\quad MBar$$

Back scattering: calorimetry

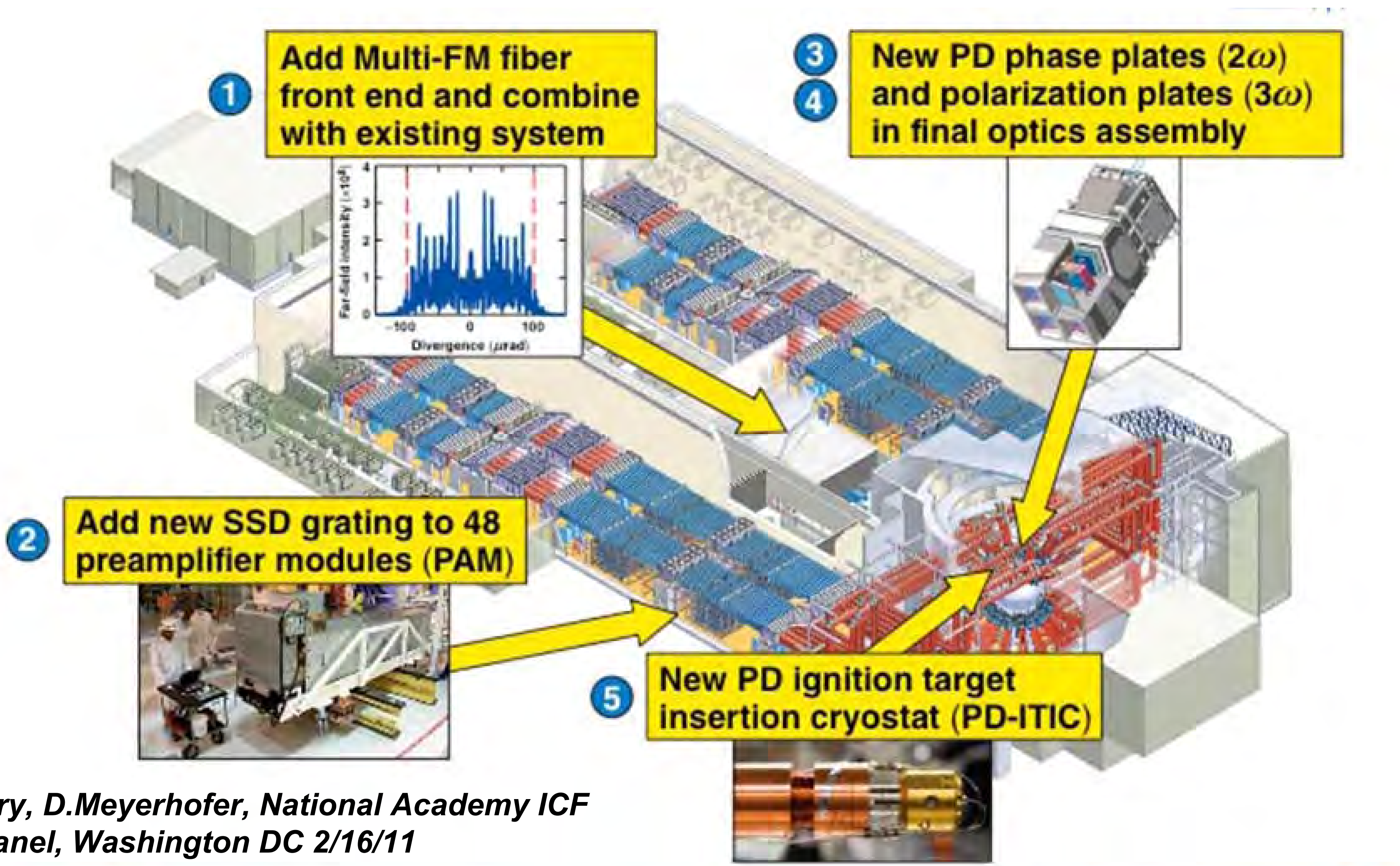
Results at the Omega facility (Usa, 2009) give 33% back reflection at I ≈ 8 10^{15} W/cm^2

A surprisingly small fraction of light is backscattered in our experimenal conditions (I ≈ 10^{16} W/cm^2, λ = 0.44 μm)



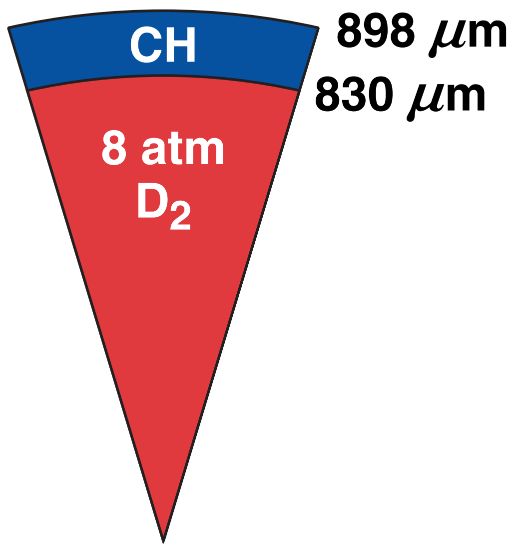
WORK IN PROGRESS...

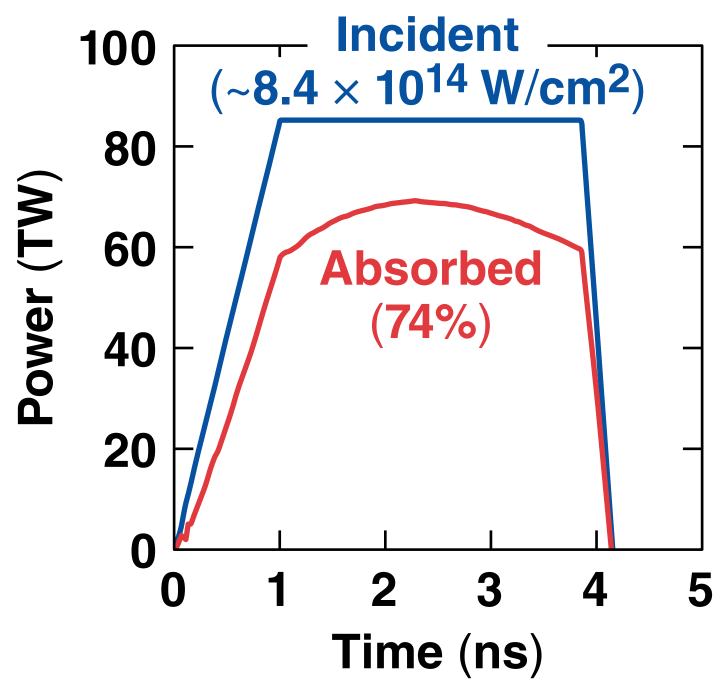
Full implementation of NIF polar drive will require five hardware upgrades for a (cryo) ignition demonstration



R.McCrory, D.Meyerhofer, National Academy ICF Target Panel, Washington DC 2/16/11

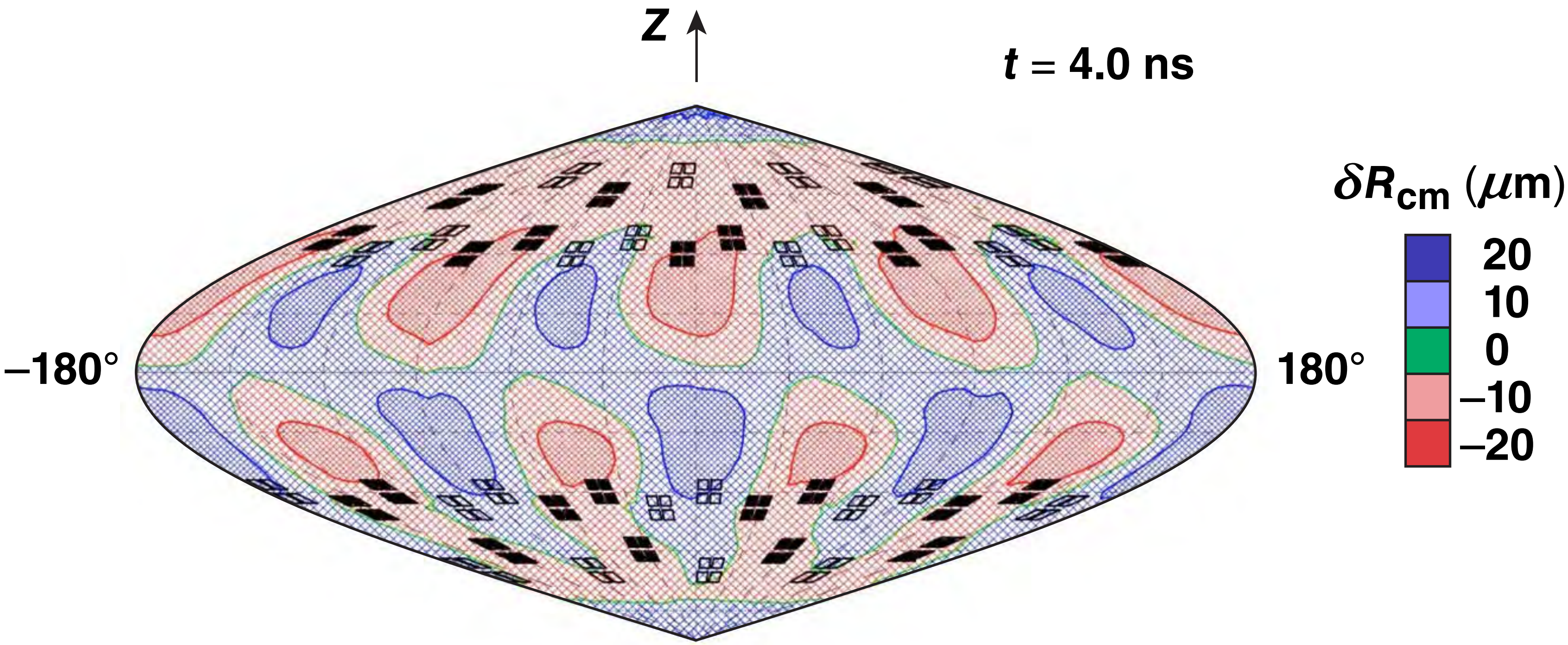
A surrogate CH target is proposed to test the 24-quad compression phase





- Objectives of the initial experiment
  - diagnose the implosion uniformity
  - measure the speed of the imploding shell
  - diagnose any hot electrons from the two-plasmon instability

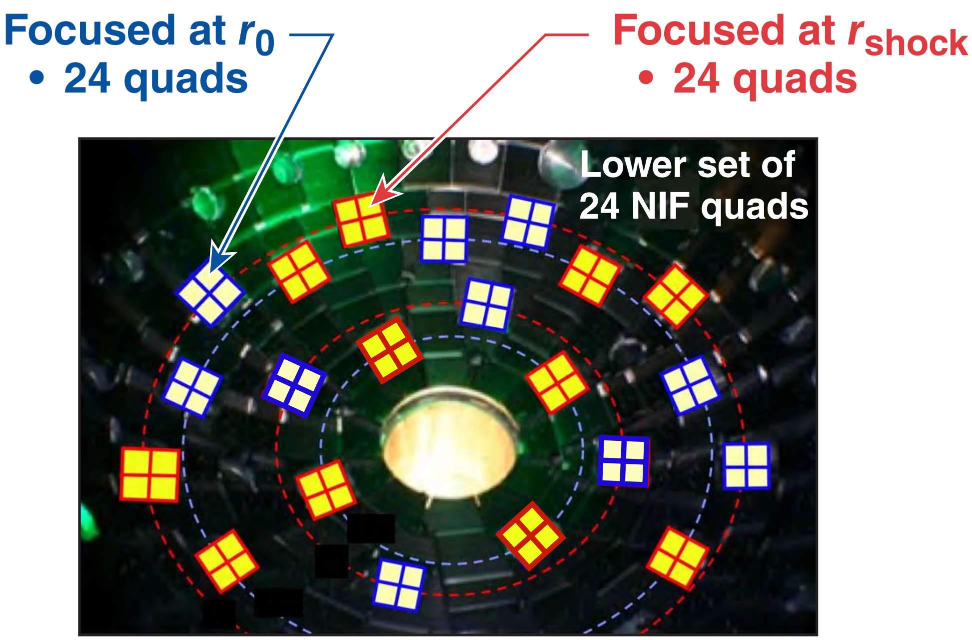
The center of mass radius is uniform to 8.1 μm (rms) when averaged over the sphere



Run 1266
TC9036

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 for better coupling of energy to the target**
- **A scheme with split quads would allow for 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**



R. S. Craxton *et al.*, Bull. Am. Phys. Soc. 55, 26 (2010).

Primary Action Items focused on Target Design and understanding the effects of LPI on target performance

UR LLE

Target Design

- Design a proof-of-principal, low-risk, low-gain SI experiment
- Determine if a planar I15, 300-MB shock experiment is possible
- Determine how we can get more energy into the spike pulse
- Design initial experiments for the NIF

LPI and the *THING* ($2\omega p$ threshold)

- Determine experimental platform to identify and mitigate preheat during the fuel-assembly phase
- Determine experimental platform to identify if single beam versus overlapped beams mitigate spike-pulse preheat
- Review STUD pulse experimental results from Trident

Direct Drive w or w/o Shock Ignition Also Requires LPI Control

Polymath Research Inc.

- If we do not keep the growth of parametric instabilities under strict control during the main pulse, then the hot electron preheat will make the final shock have dubious prospects.

- Worry about SRS and $2\omega_p$ as the two most likely hot electron generating instabilities via their plasma waves daughter waves.

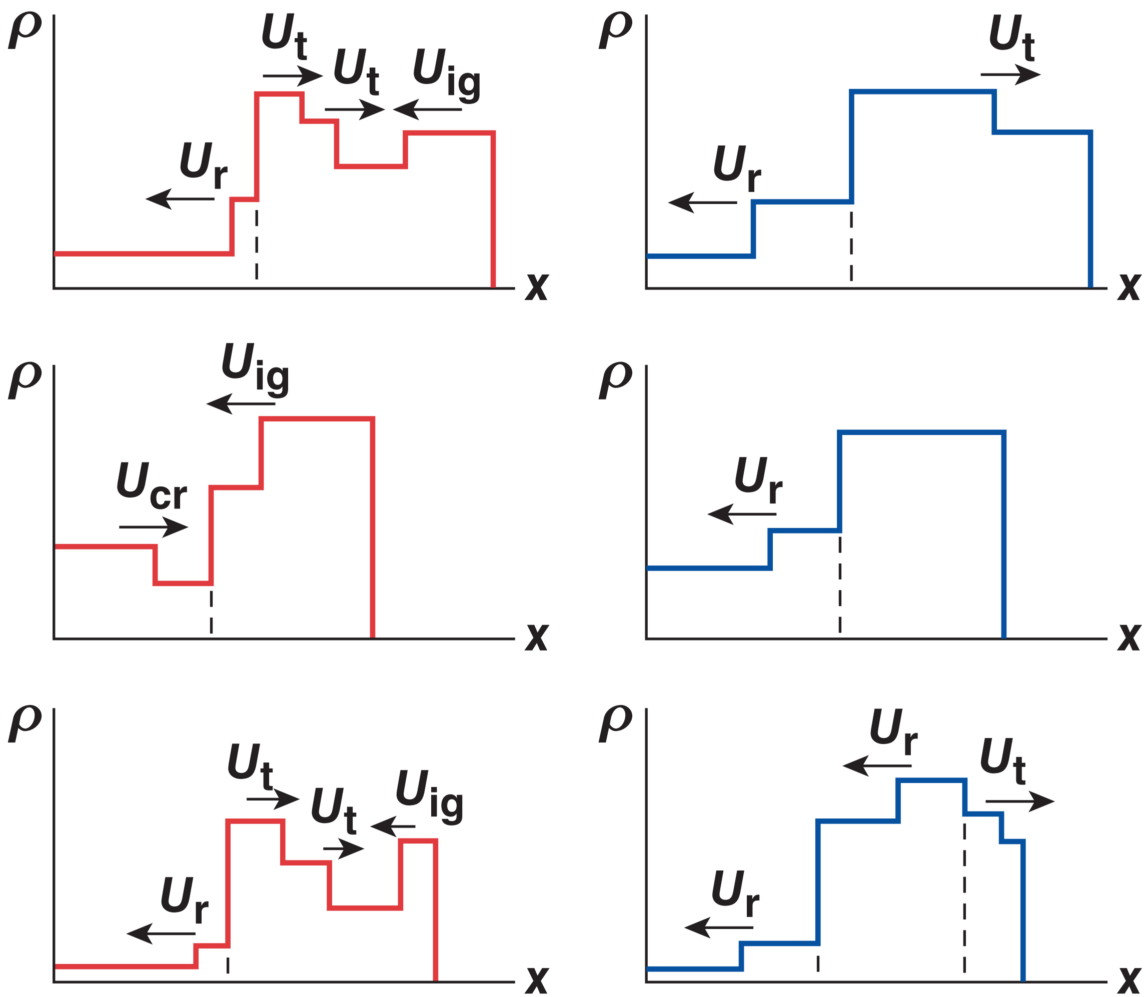
- Worry about the physics of multiple of massively overlapping beams, hot spots overlapping, triggering each other's instabilities, nonlocal influences in space, mediated by hot electrons, secondary instabilities, SRS/SBS anti-correlation, ...

- This is not your grandfather's LPI scenario.

- For shock ignition, need to convert the right distribution of hot e^-s into a sharp heat front that becomes that last shock, quickly assembled. Designing this is a wonderful challenge of our knowledge of LPI physics.

- What wavelength to use for the last shock, what pulse shape, what intensity regime, all remain open and exciting questions.

Late shocks can suppress rarefaction waves—there are three ways shocks can be launched



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

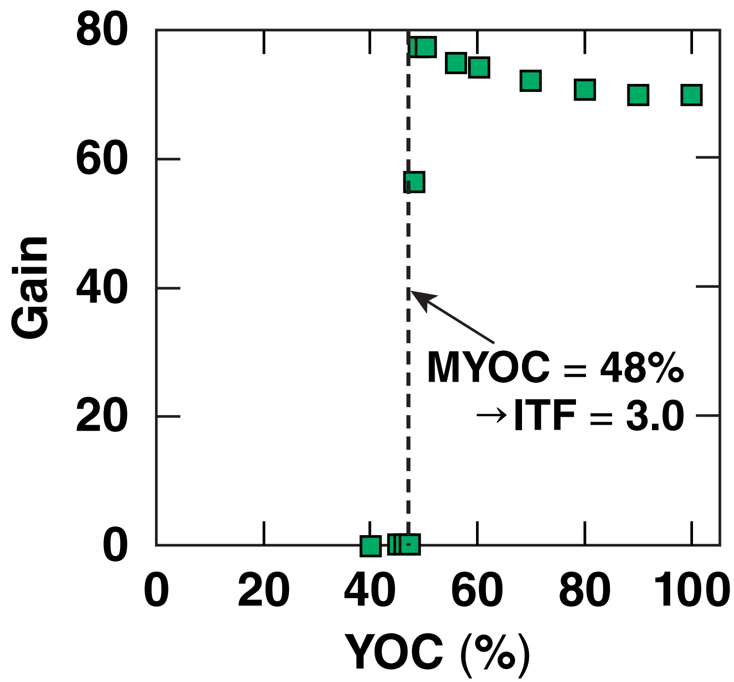
No-transmission technique
(requires one moderate shock)

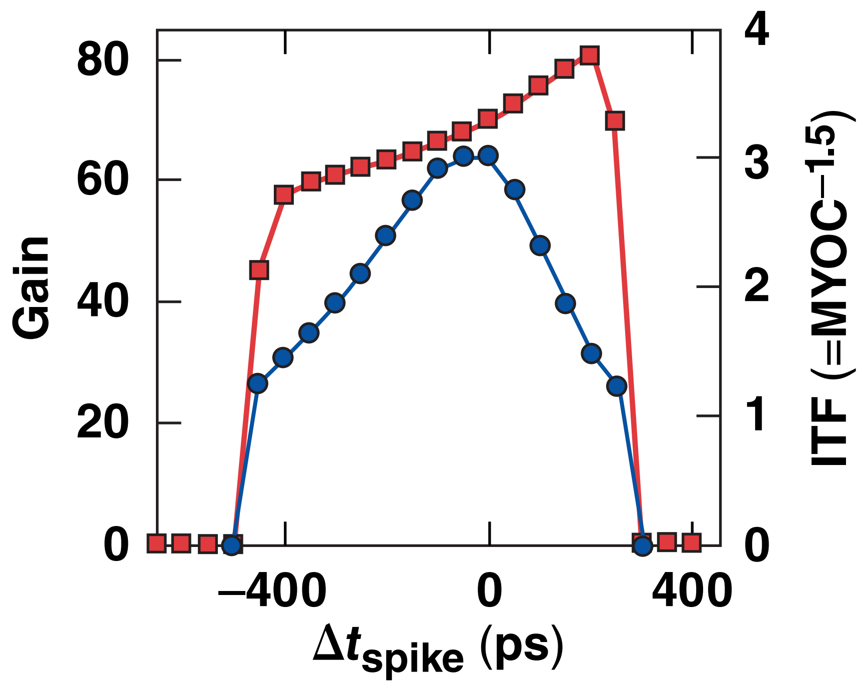
Re-shock technique
(requires one strong shock)

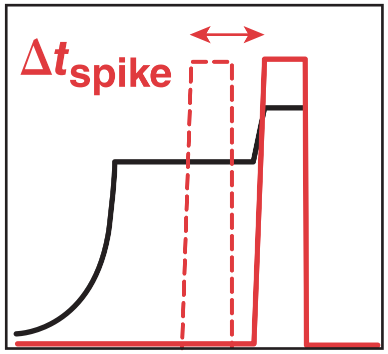
TC9191

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

Plastic-ablator shock-ignition targets are robust to shock timing and reduced clean volumes



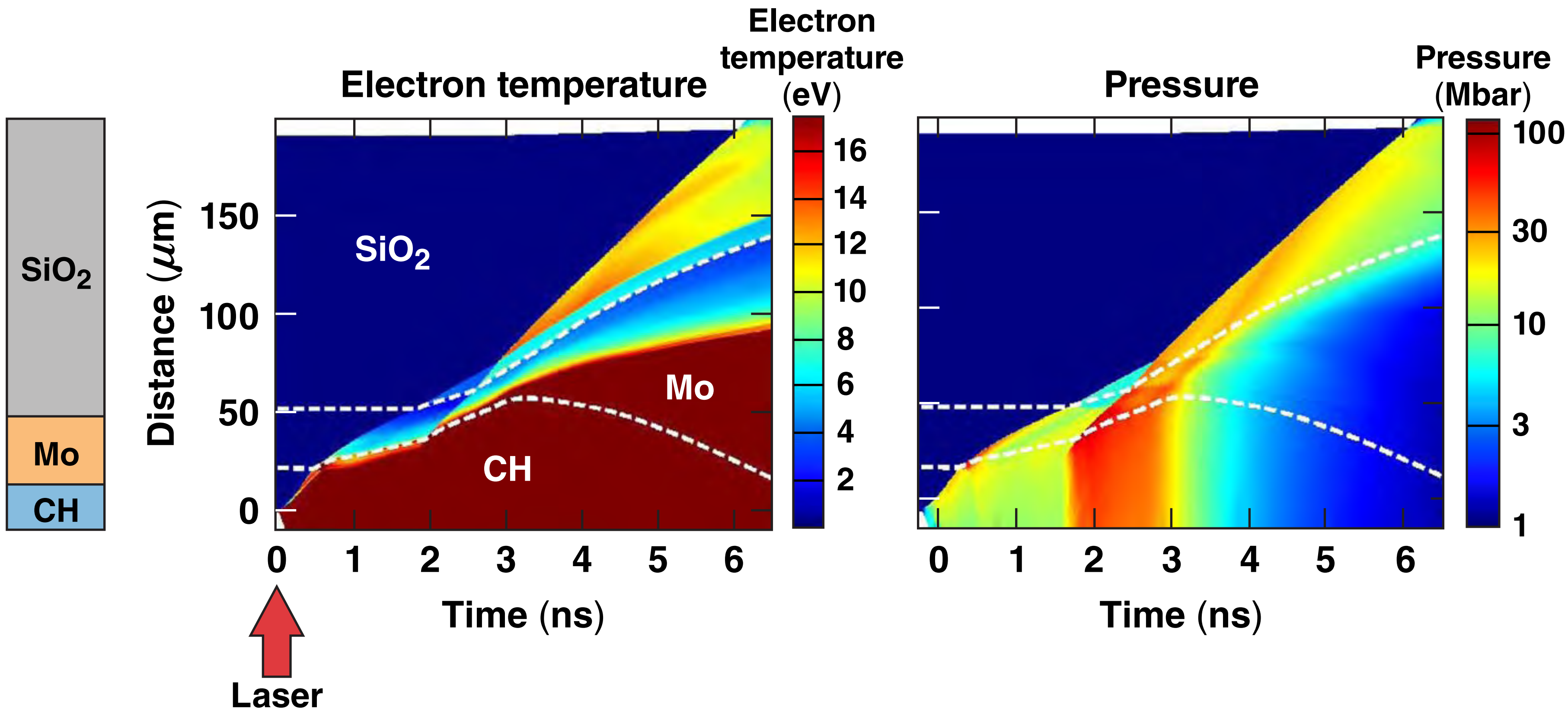




ITF for indirect-drive point design* is ~5.3 (MYOC = 33%) at 1 MJ.

*J. Lindl, presented to the JASON Review Committee Study #JSR-09-330, San Diego, CA, 14–16 January 2009.

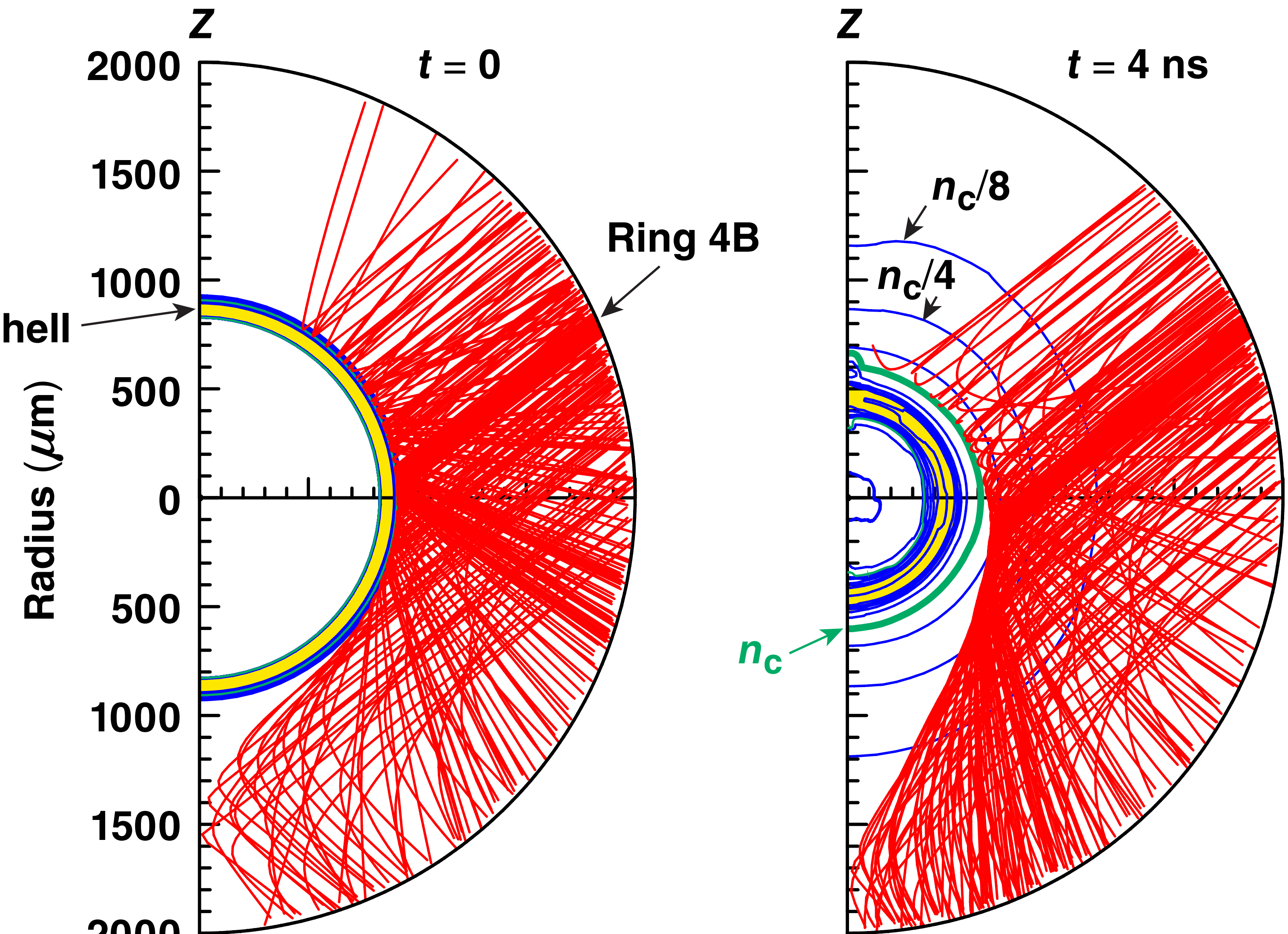
1-D hydrodynamic simulations predict an initial plasma pressure of ~100 Mbar for ~1 × 10^{15} W/cm^2



- The spike absorption is varied to match the shock-breakout time
- 2-D *DRACO* simulations are currently being performed

TC9072a

The CH shell implodes uniformly throughout the 4-ns laser pulse



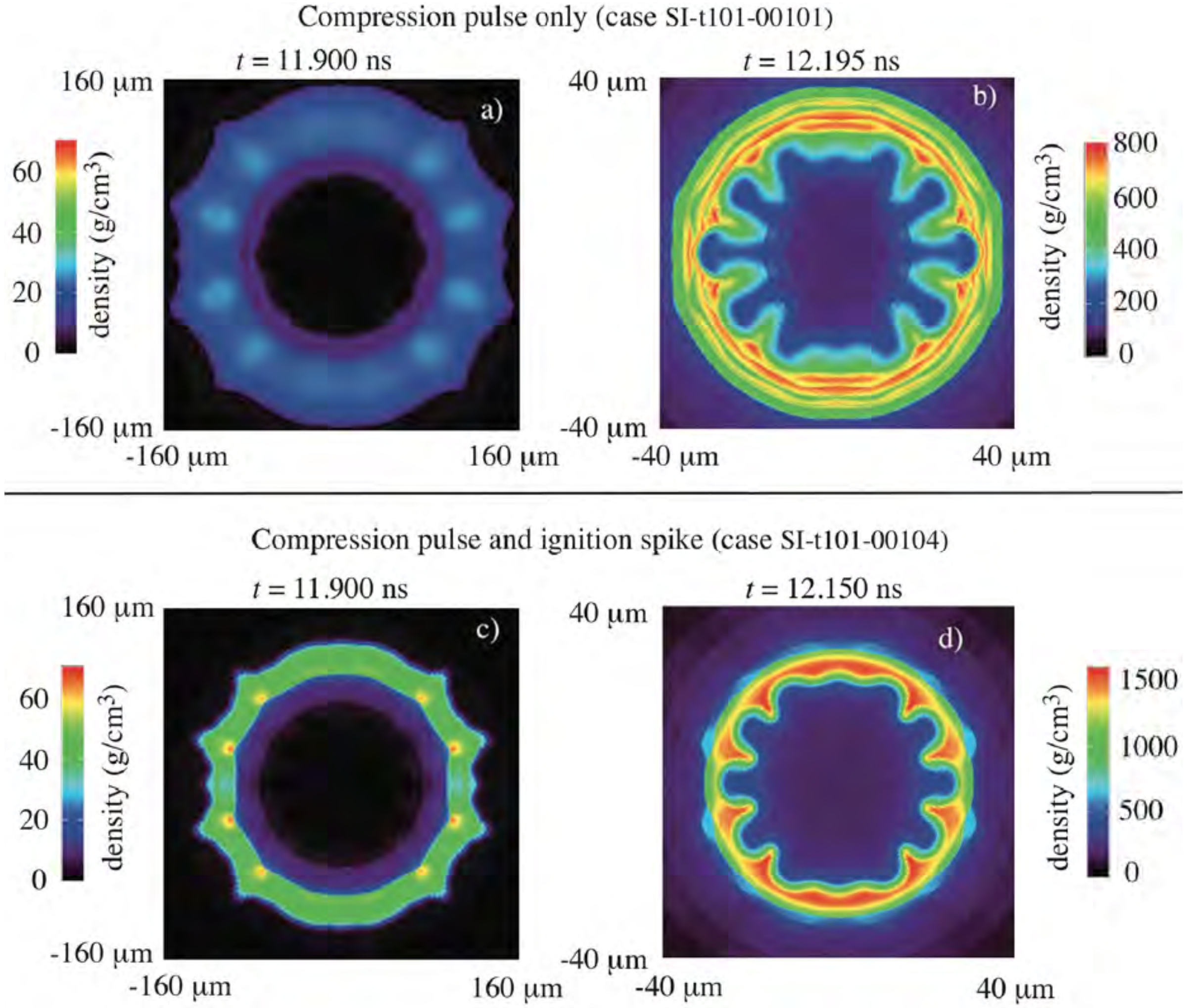
Run 1266
TC9032

Shock-ignition: reduced hot spot-RTI growth

No SI spike

with the
CELIA
rradiation
spectrum

Shock ignition



perturbation growth halts
@ shock collision

S. Atzeni, A. Schiavi, A. Marocchino, PPCF 2011.; confirms results by Ribeyre et al. PPCF 2009

Doubling the outer surface perturbations causes gain failure

NRL

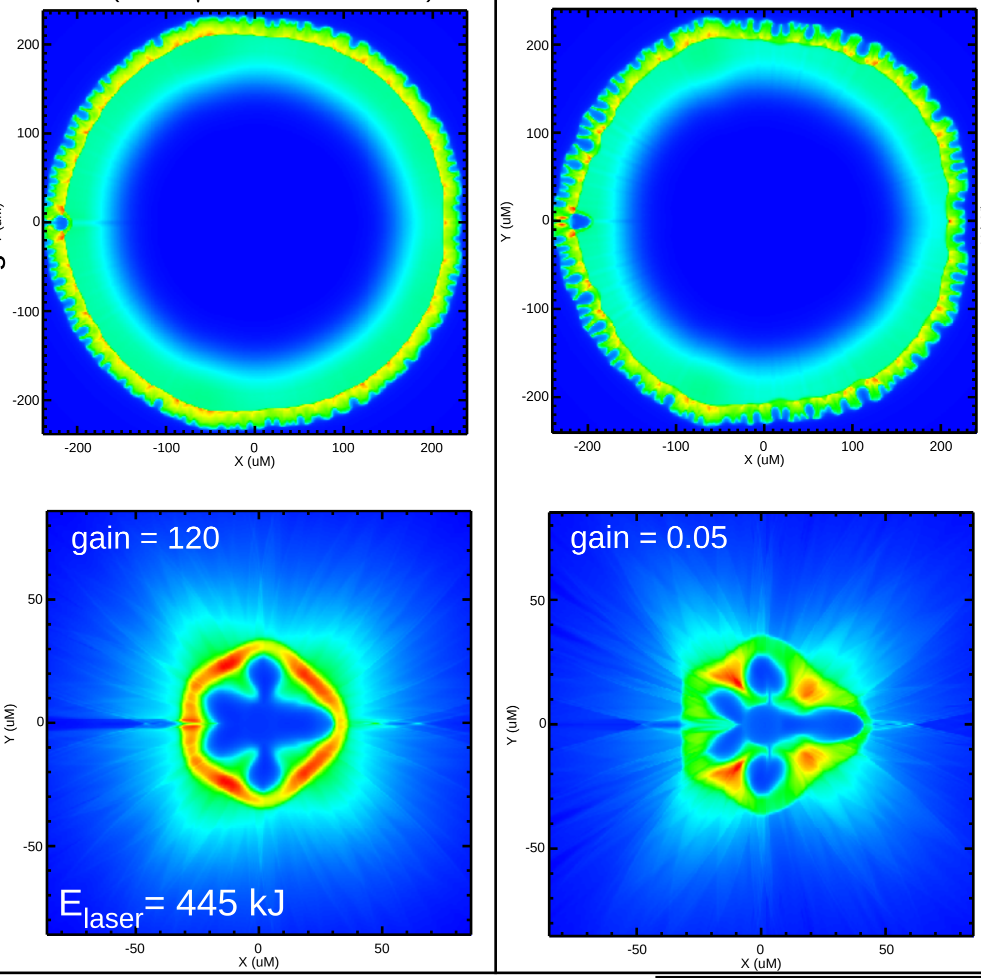
broken:
doubling the surface roughness prevents ignition and gain

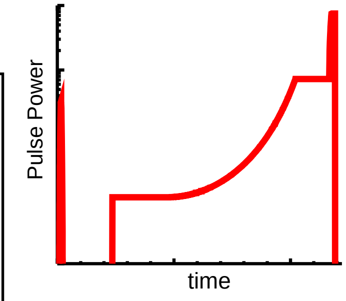
“1xNIF”
0.49 µm rms outer surface
(=0.15 µm rms in solid CH)

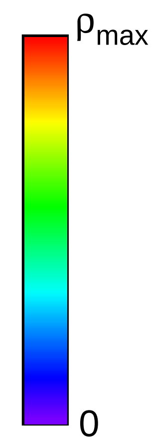
“2xNIF”
spike power (750TW)

16.4 ns
after ignitor shock launch

16.89 ns
as burn begins

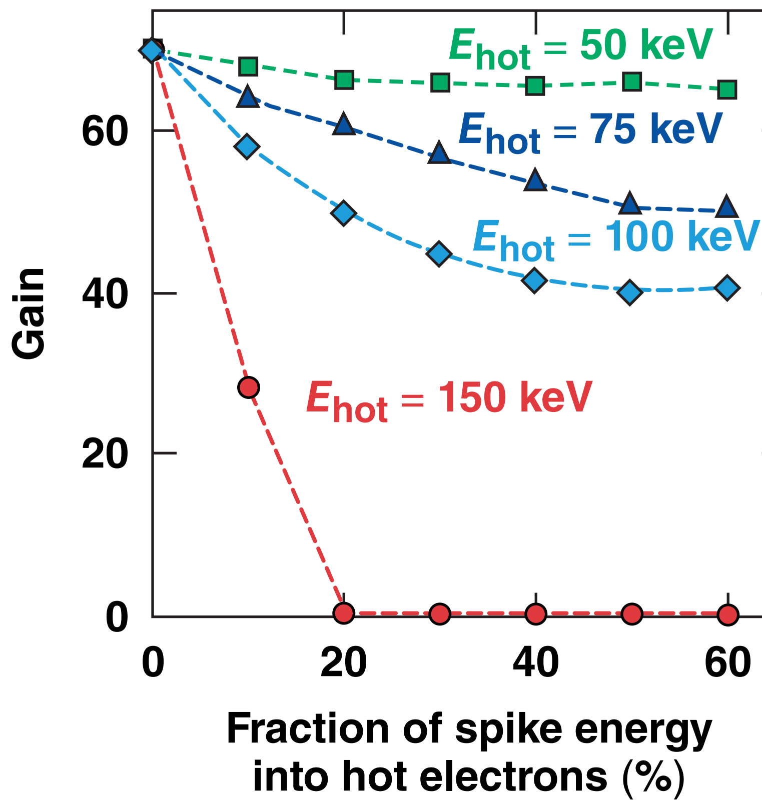






scale 2 target

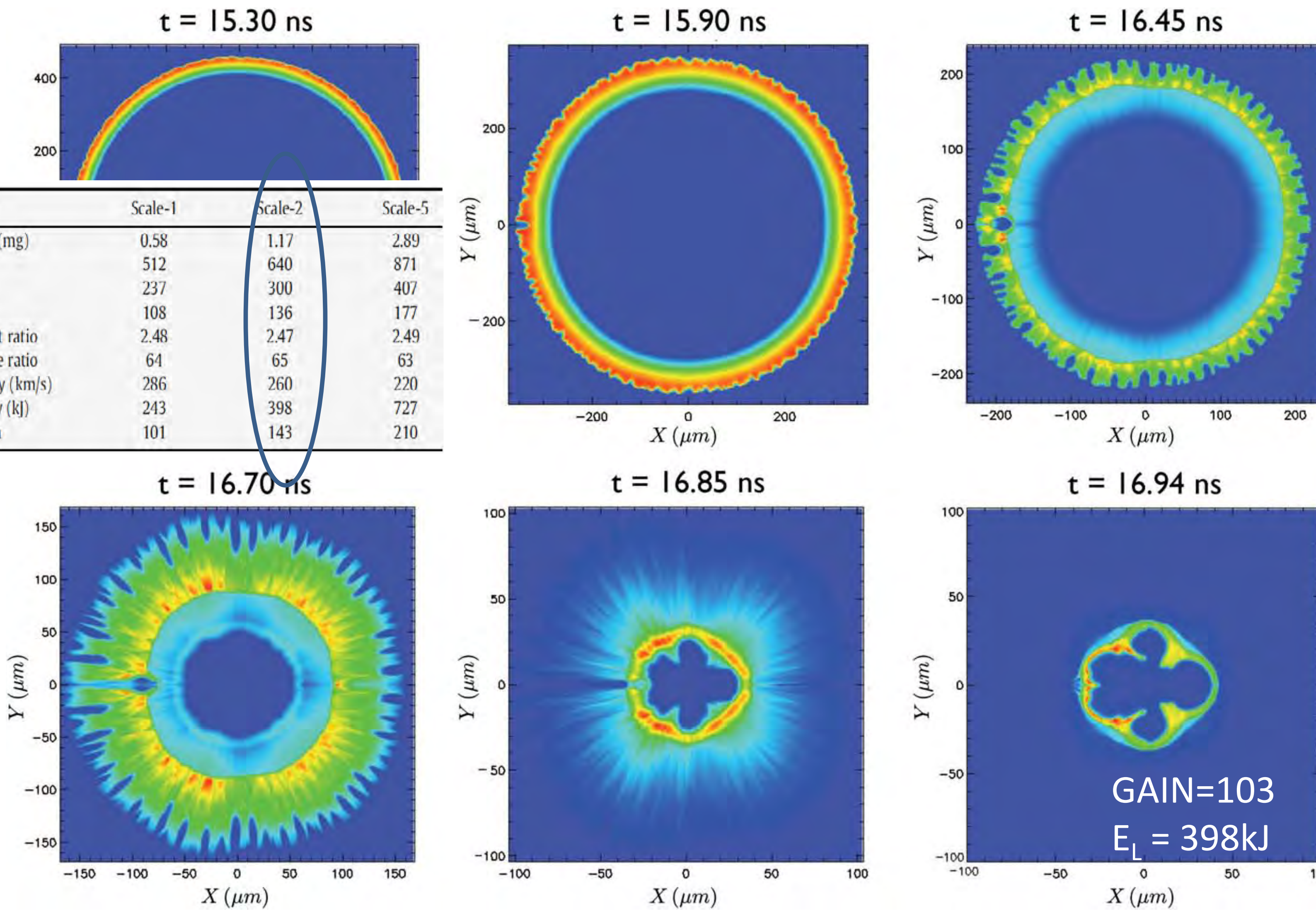
The plastic-ablator SI design is robust to hot electrons up to 100 keV at 60% of laser energy during the spike pulse



- Straight line hot-electron-transport model by A. A. Solodov
- Future work will investigate hot-electron transport during the main pulse

TC9111

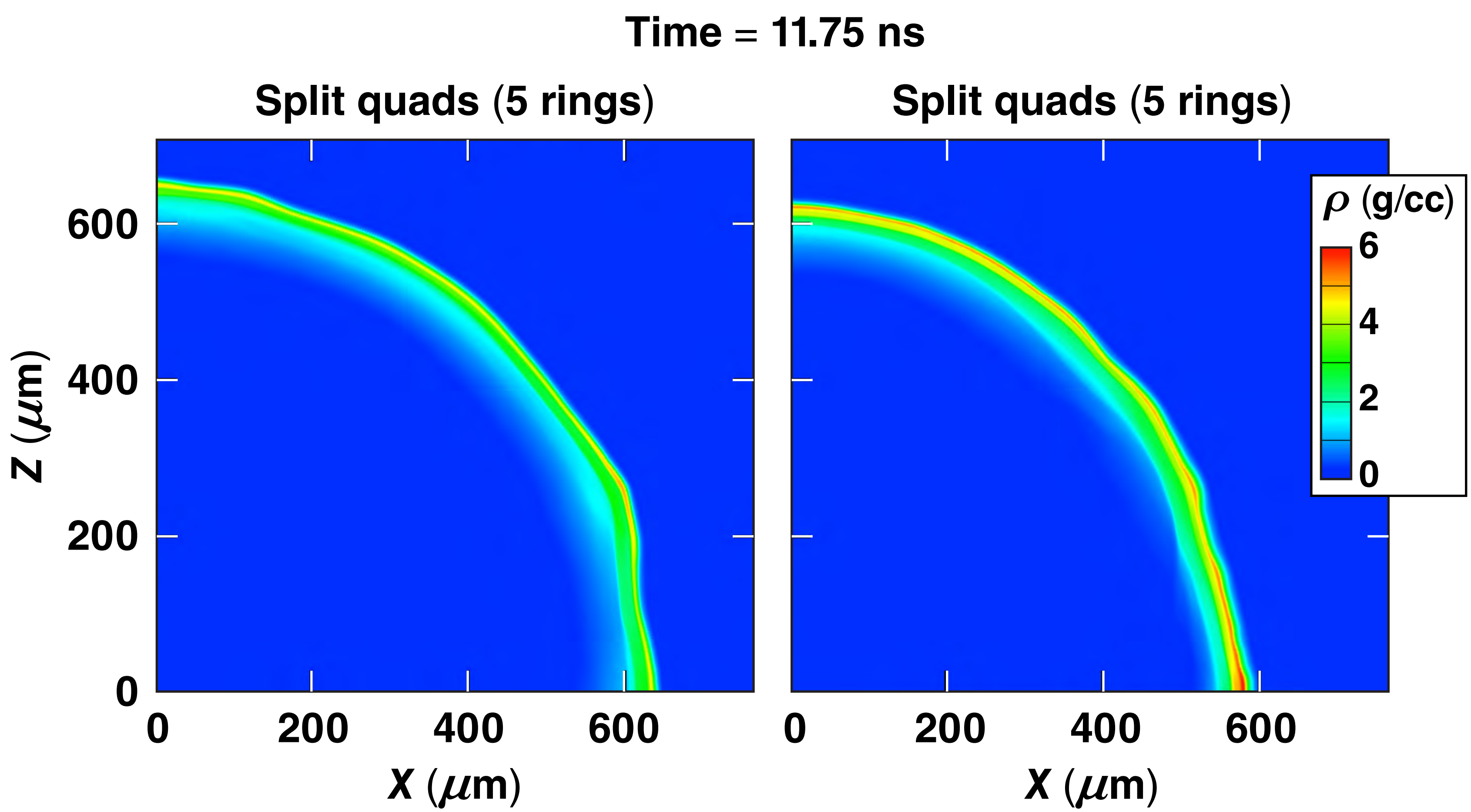
Comprehensive 2D simulations of SI KrF targets, with zooming are carried out by the NRL group



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)

Preliminary *DRACO* polar-drive shock-ignition simulations indicate reasonable uniformity, but refinements are needed



Laser-imprint studies are also in progress.

TC9305

Laser Plasma Interactions: Late time SRS generated by the shock is probably benign and may be beneficial to the shock drive

- **Early time 2ωp hot electrons are main concern (near-term experiments?)**
- **SRS/2ωp hot electrons generated by high intensity shock may:**
  - (will) be absorbed in outside of dense converging shell
  - improve the ablation process?
  - provide good ablative stabilization ?
  - contribute to symmetric shock drive by long mfp smoothing?
  - permit effective drive at 2□ (green)?
- **Efficiency, symmetry and stability of shock coupling is a paramount research issue (near-term experiments?)**