Studies of high gain target designs at NRL*

International Shock Ignition Workshop

Rochester, NY
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presented by

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*on behalf of the **NIKE/Electra** team*

*supported by US Navy and DoE/NNSA

Overview: shock ignition targets designed for high gain with KrF

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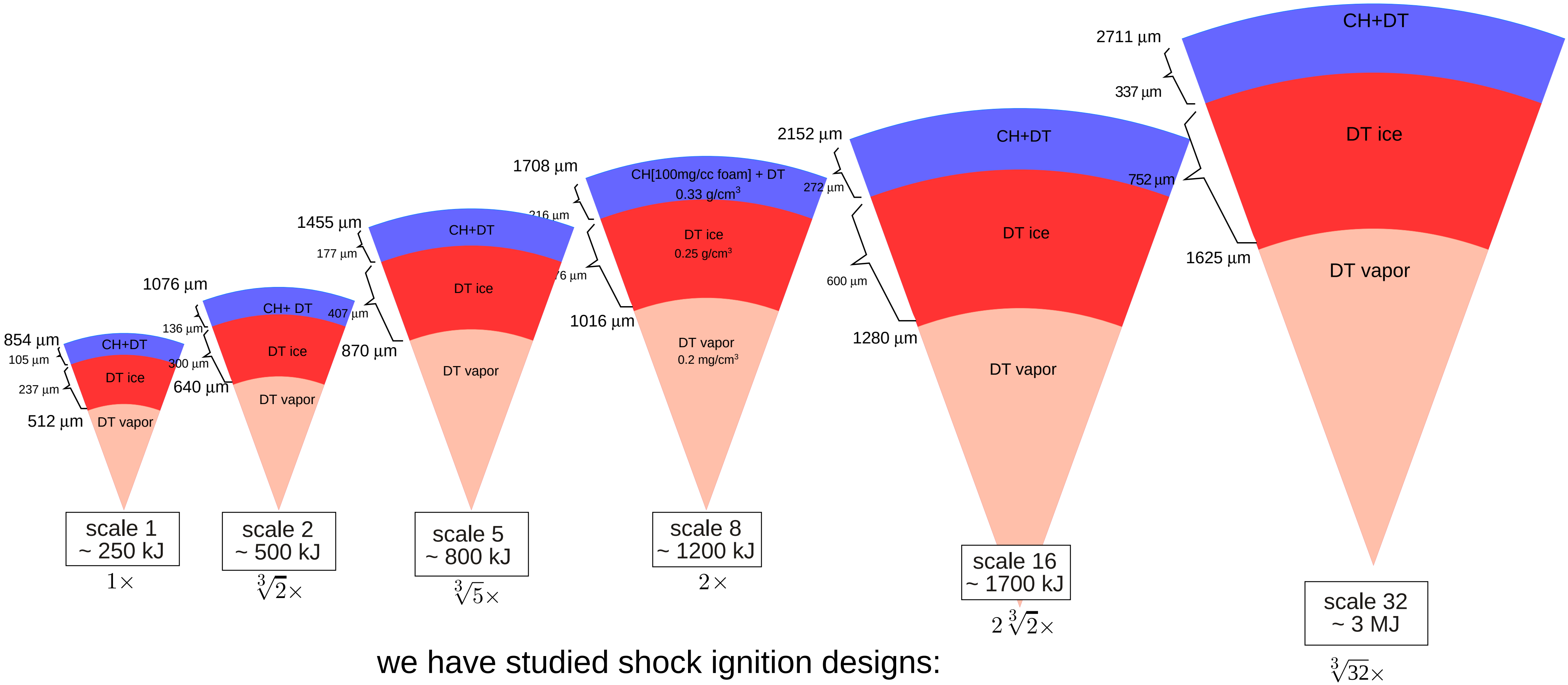
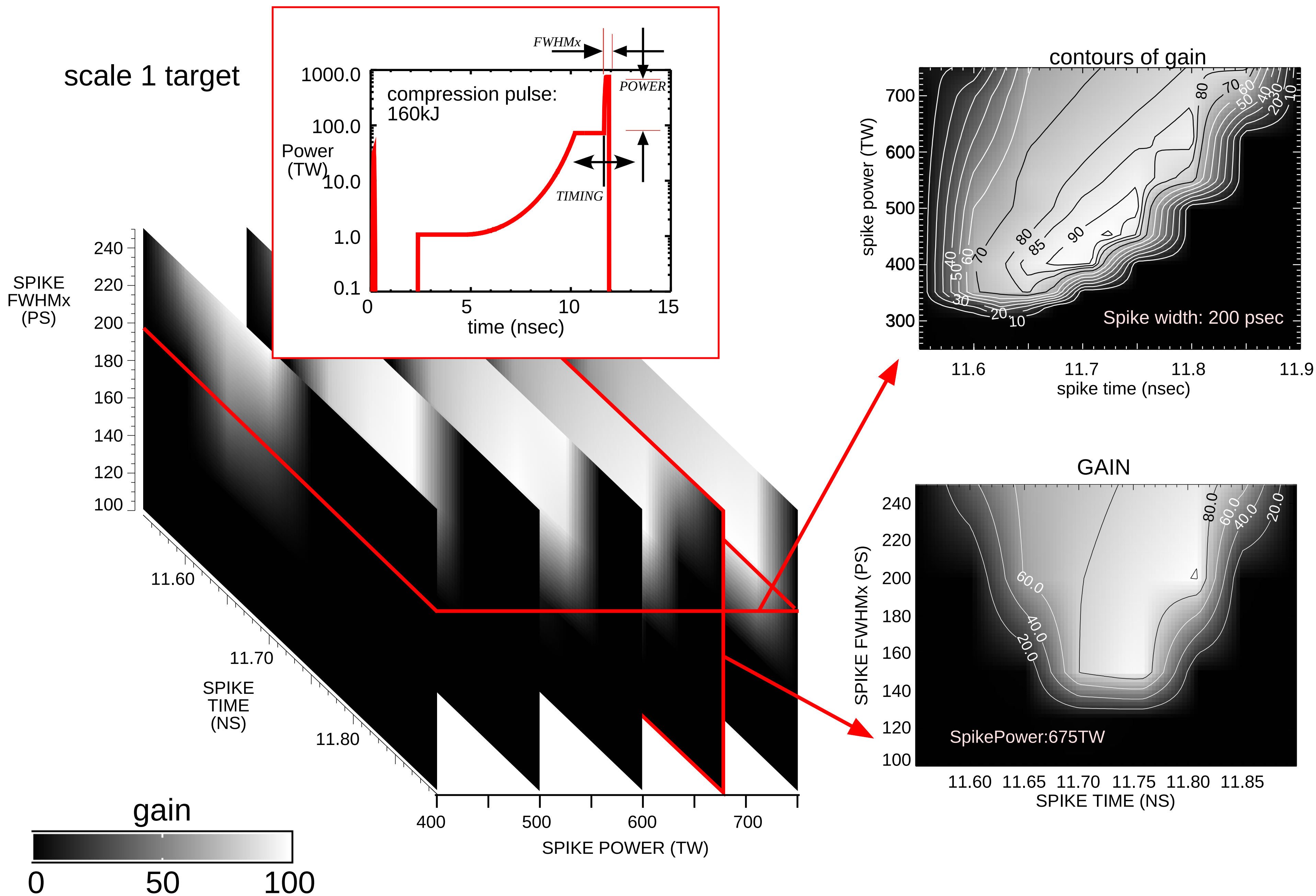


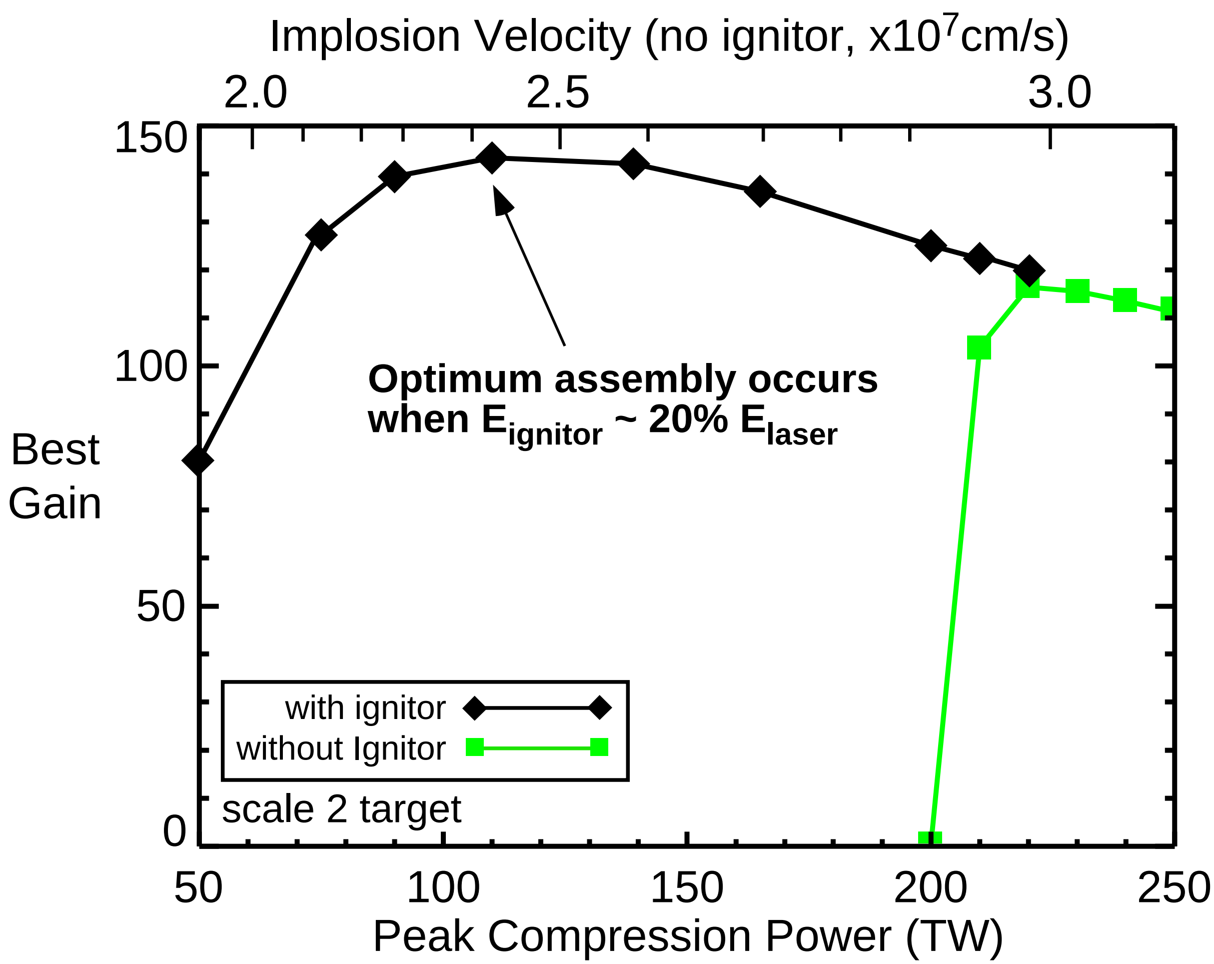
we have studied shock ignition designs:

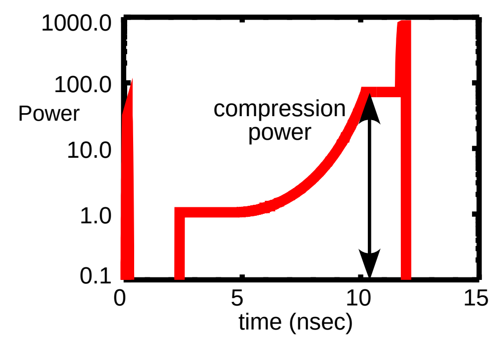
- low-aspect (AR=2.5) foam/DT targets
- driven by 248 nm KrF light
- laser spot size is zoomed twice
- target mass varied by a scale factor of 32
  (scale 1 = ~250 kJ - scale 32 = ~3 MJ targets)
- target adiabat is kept moderately low (α~2)

Extensive 1D runs map out the parameter range for shock ignition targets



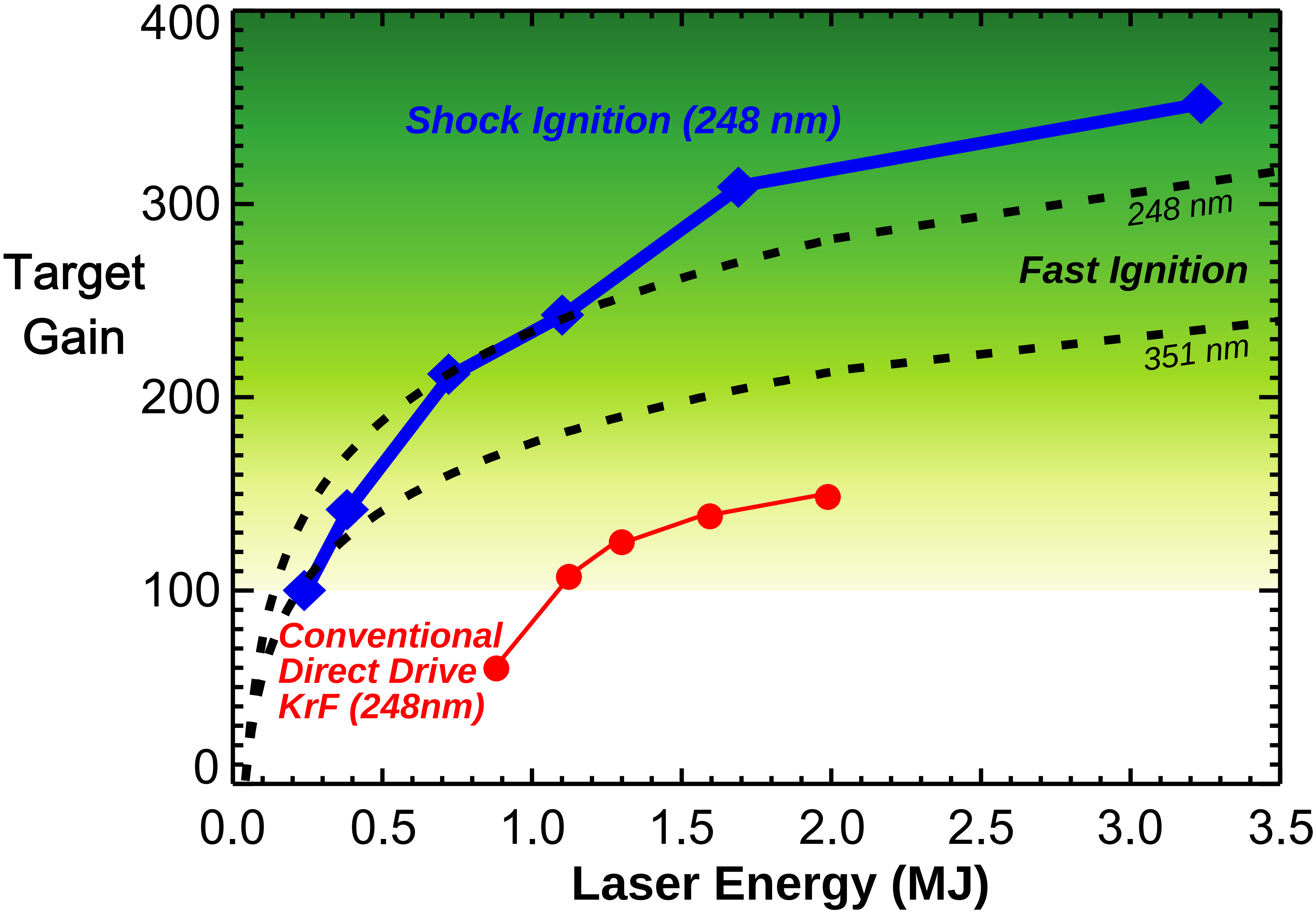
The process is repeated for different compression powers, and an optimized gain if found for a particular target





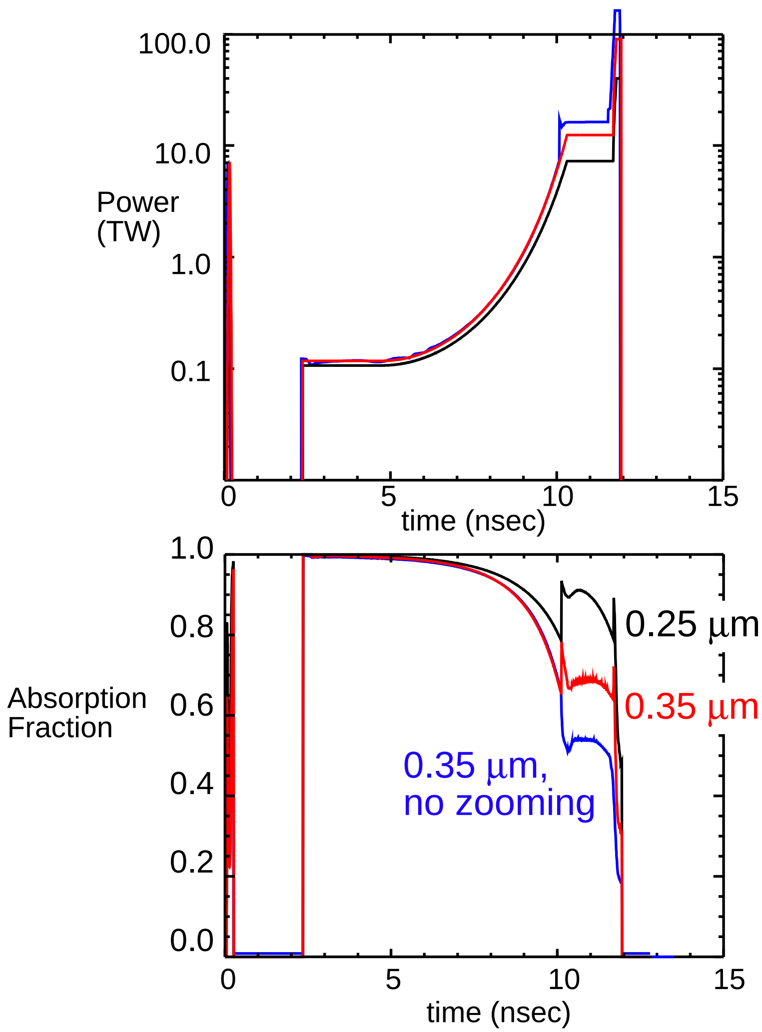
A.J. Schmitt et al., Phys. Plasmas ***17****, 042701 (2010)*

The process is repeated for each target and produces a gain curve



The shorter wavelength and zooming give a significant advantage to targets driven by KrF light

The scale 1 target was simulated with frequency-tripled Nd:glass laser drive; the pulse shape was changed so the drive pressure was the same.

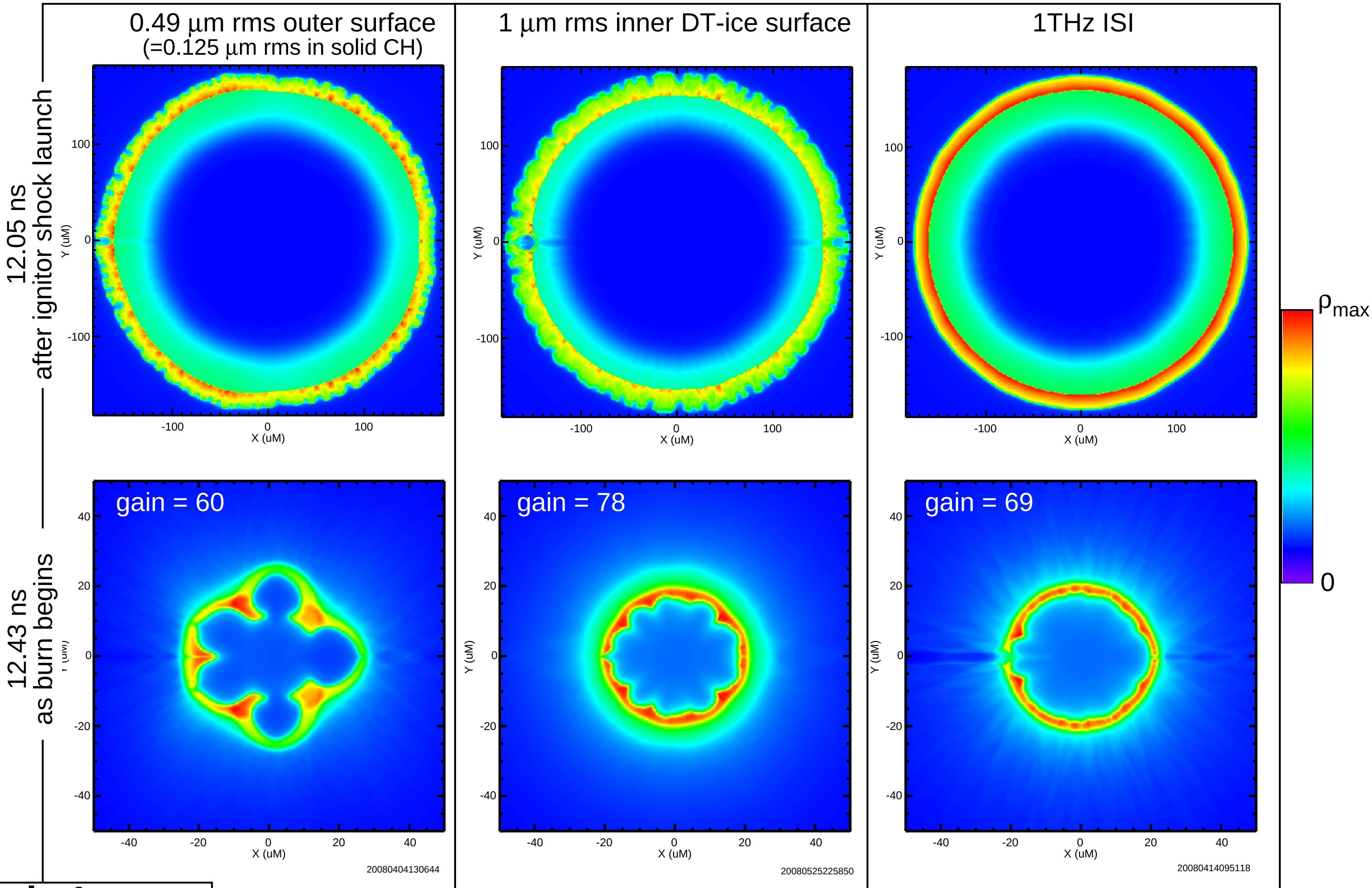


	KrF 0.25 µm zoom	glass 0.35 µm zoom	glass 0.35 µm no zoom
total energy	230 kJ	430 kJ	645 kJ
compression energy	160 kJ	280 kJ	360 kJ
gain	97	56	35
absorption	77%	56%	39%
compression absorpt.	87%	70%	55%
max. intensity (PW/cm^2)	16.3	28	21.8
$I/I_{2\omega pe\_thresh}$	2.0-2.8	3.8-4.4	4.0-4.7

$$\text{pressure} \sim I_{abs}^{0.7}\lambda^{-0.25}$$

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

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



scale 1 target

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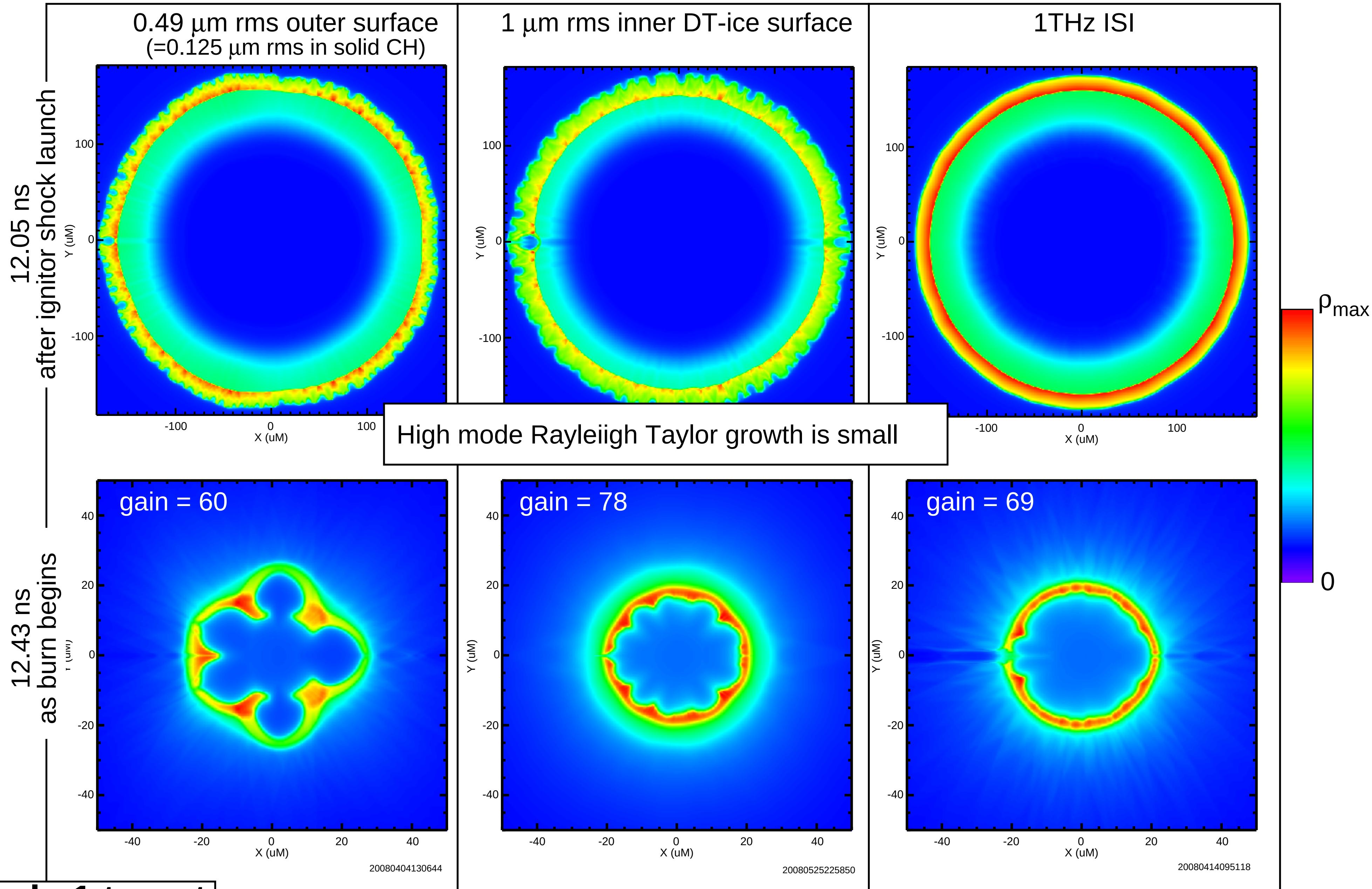

scale 1 target

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

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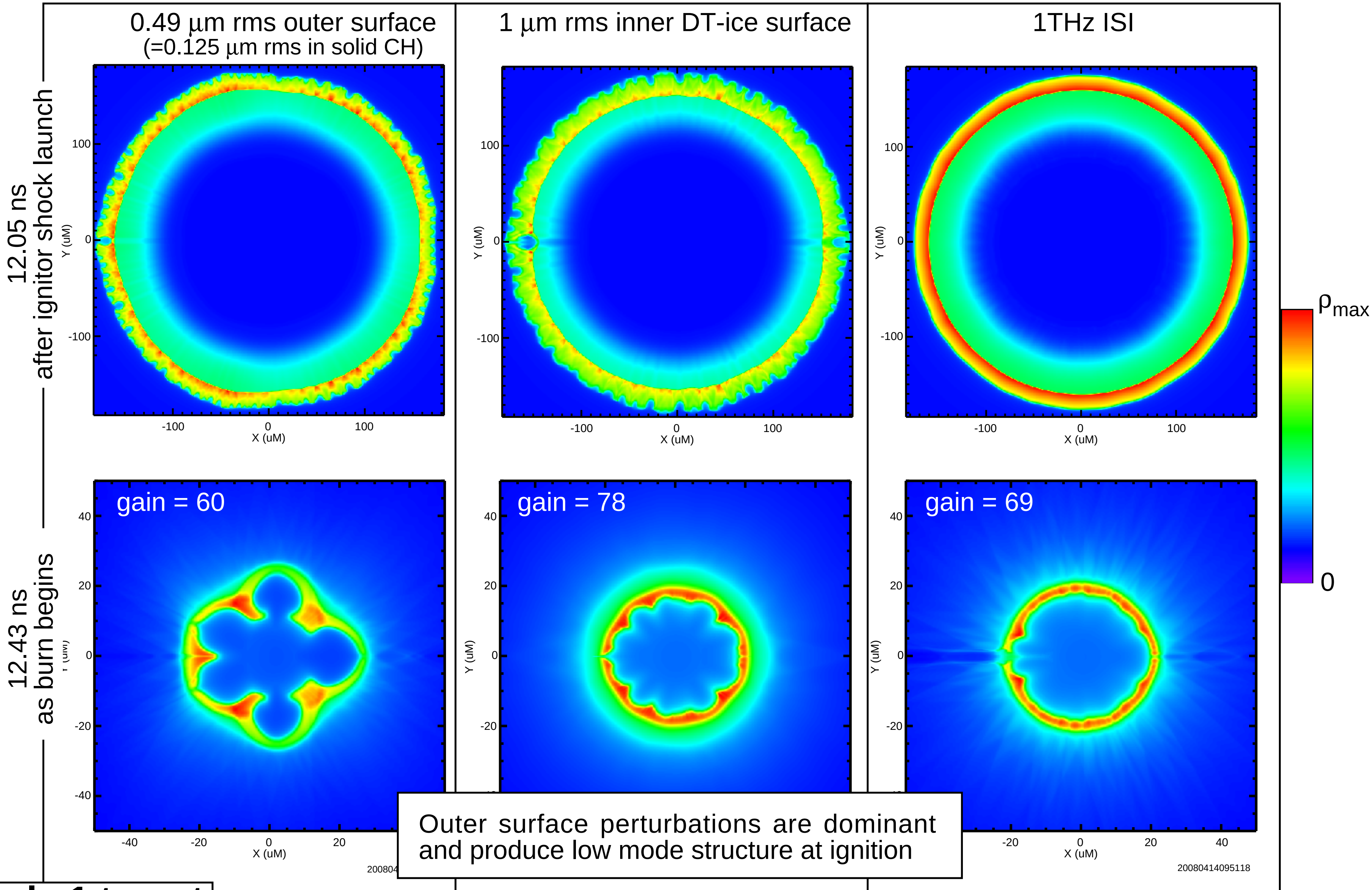


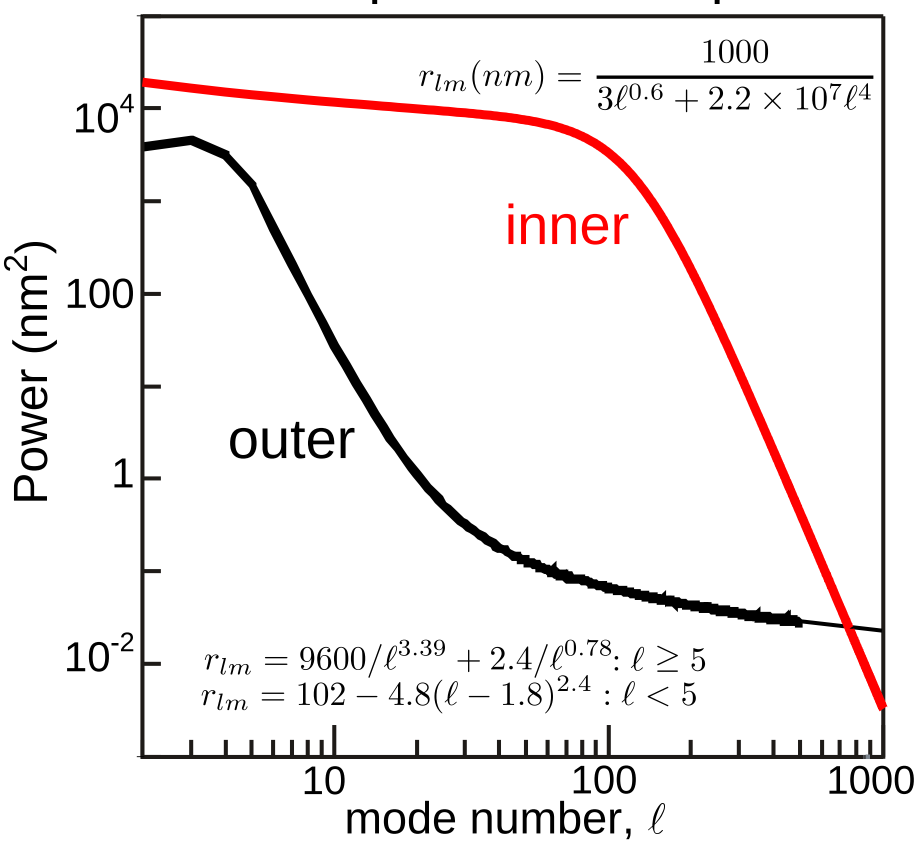
Outer surface perturbations are dominant and produce low mode structure at ignition

scale 1 target

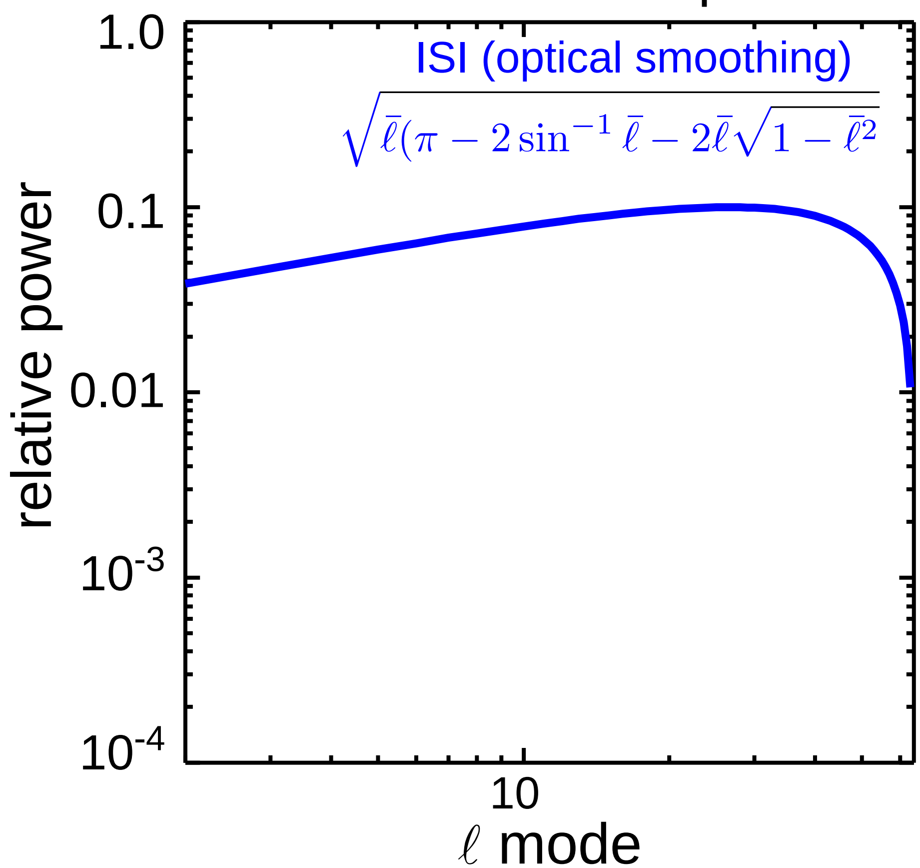
Final structure of perturbations reflects applied structure

- Outer surface spectra is dominated by low modes
- inner surface perturbation has a flatter low-mode spectrum,
  isn’t amplified until feed-out, and doesn’t get pushed as far
- laser imprint has flat spectrum and is reduced by large number of beam overlaps

surface perturbation spectra



laser illumination spectra



The target is robust to inner surface DT-ice perturbations

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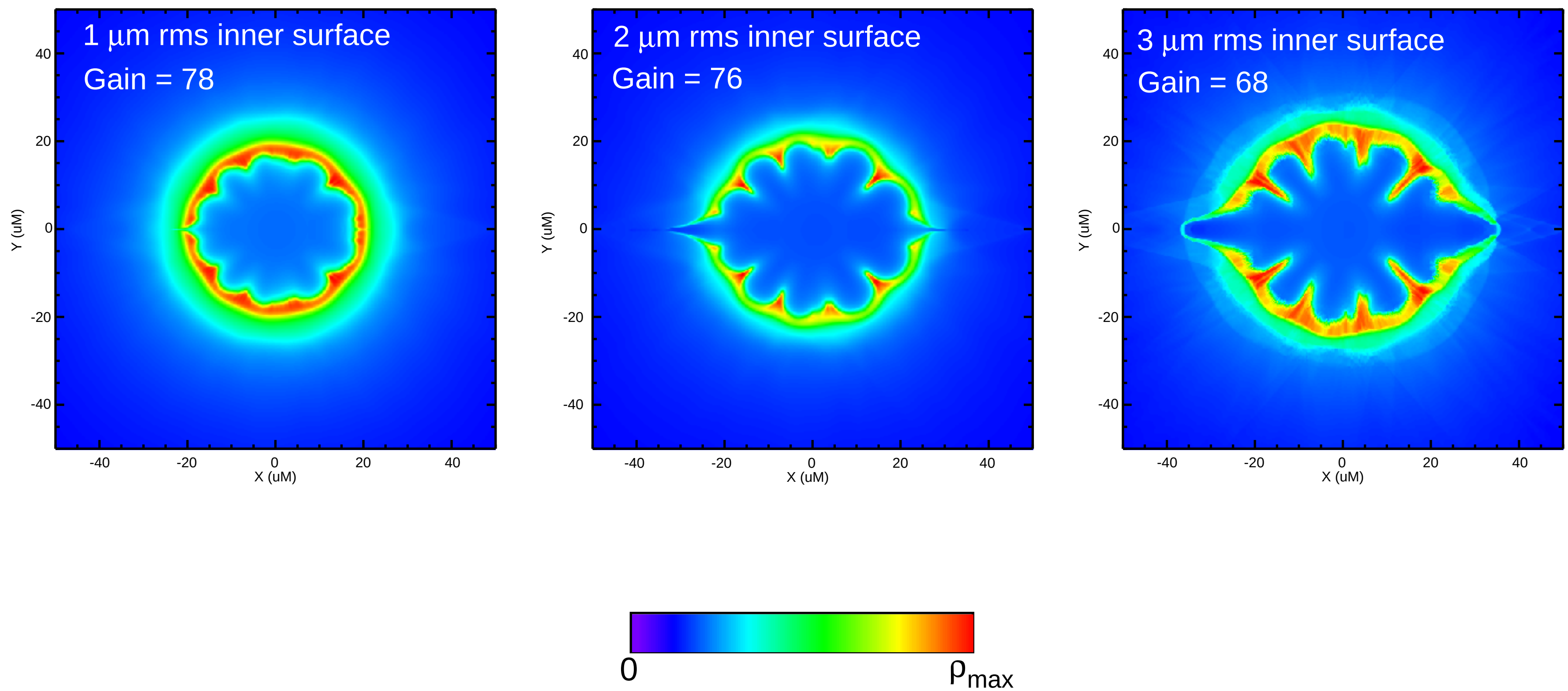
densities shown as pellet ignites



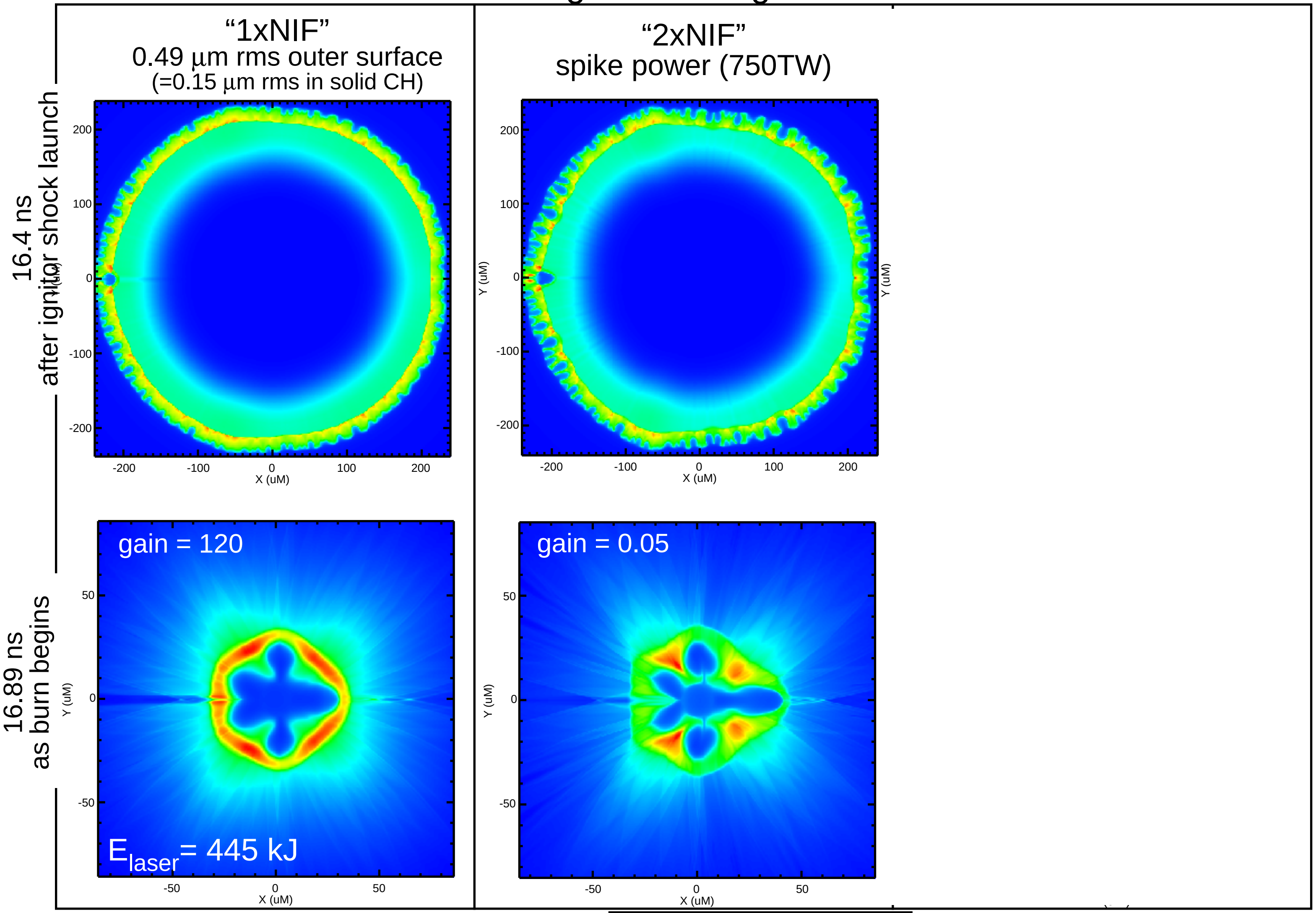
1-3 μm rms perturbations survive with near 1D yield

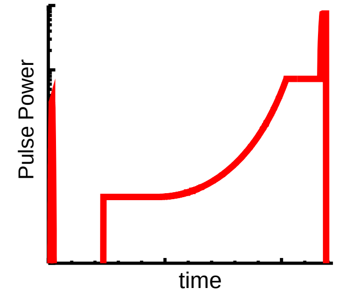
scale 1 target

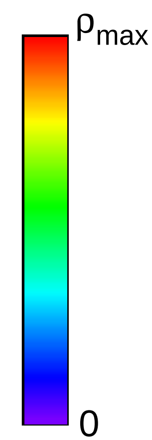
2D High-resolution simulations (ℓ=1-256)

Doubling the outer surface perturbations causes gain failure

broken:
doubling the surface roughness prevents ignition and gain





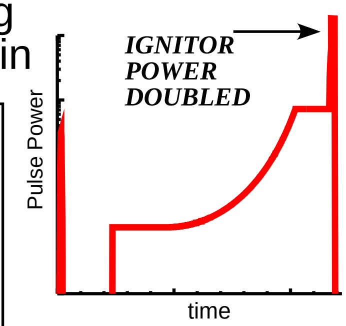


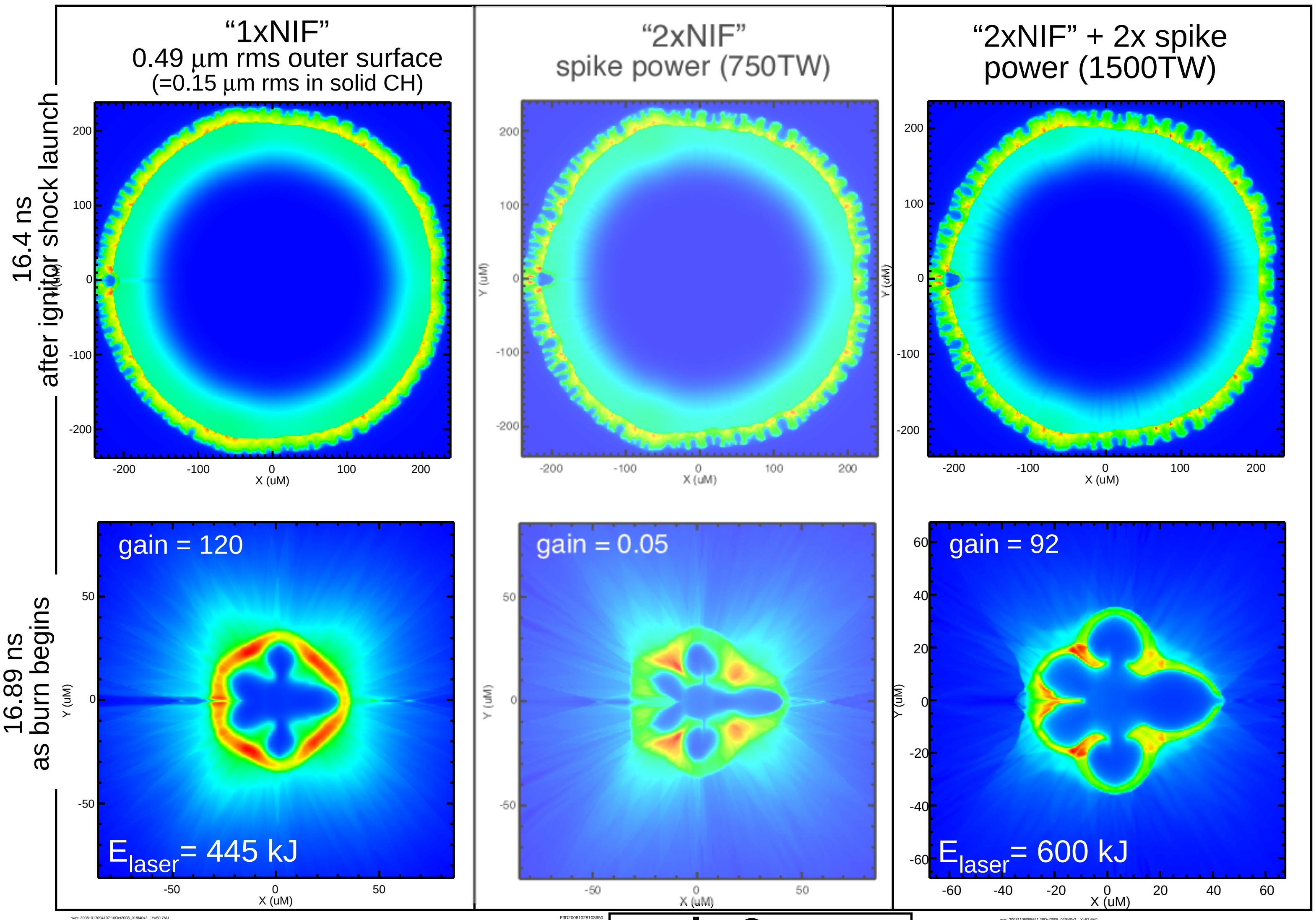
scale 2 target

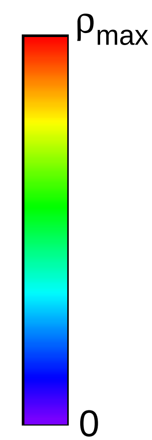
2D High-resolution simulations (ℓ=1-256)

...But increasing the ignitor power restores significant gain

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



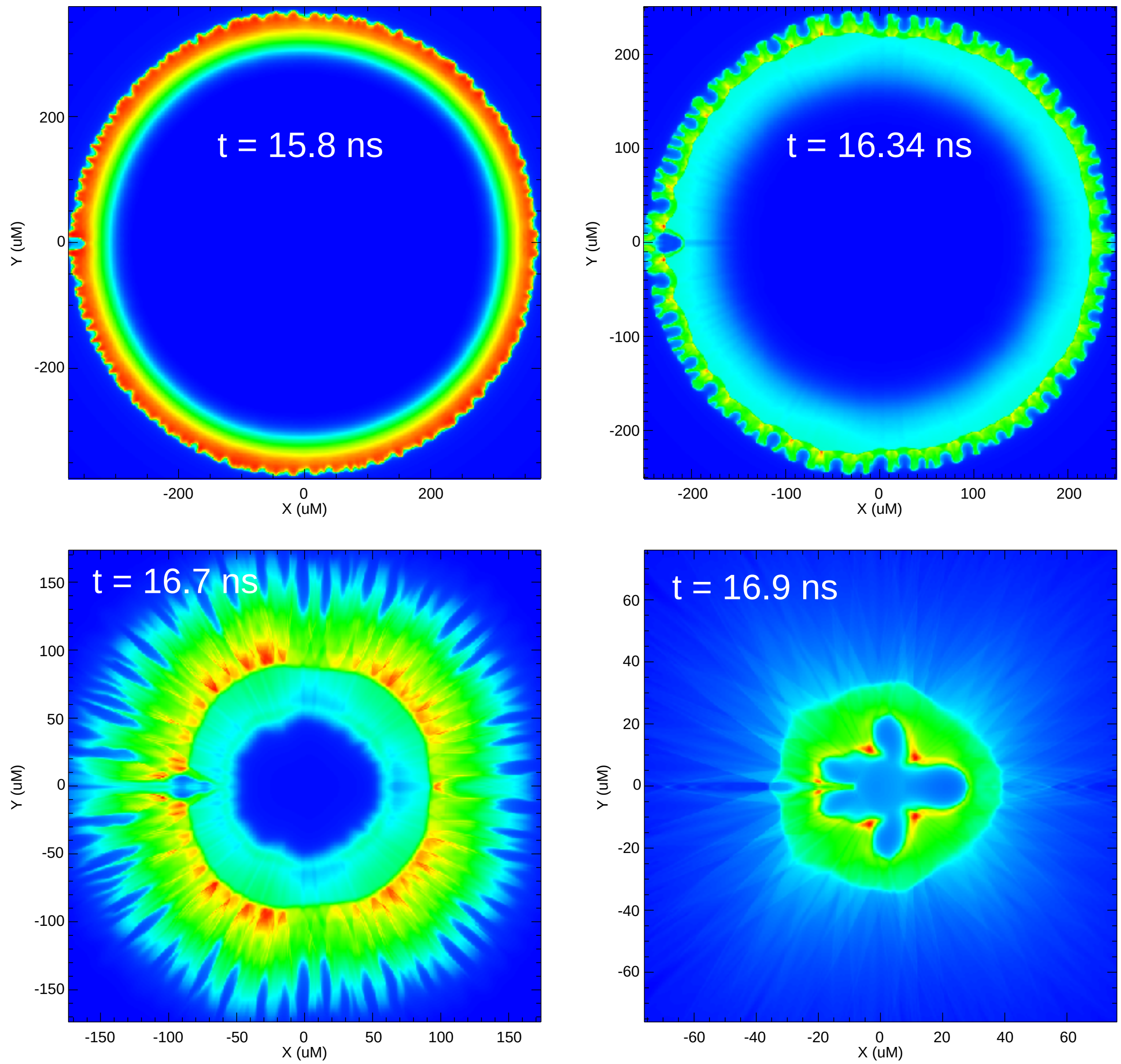




scale 2 target

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

The target survives nominal inner, outer surface finishes + laser imprint combined and maintains high gain



nominal surface finishes
(0.48 μm on wicked-foam,
1 μm in inner DT ice)
+ 1*THz*, 300 beam ISI

521 kJ KrF pulse
compression:
110 TW, 1.7 nsec
ignitor spike:
750 TW, 300 psec

Gain = 102

(1D Gain = 142)

scale 2 target

20090416150021:14Apr2009_01/SI500..; Y=53.1MJ

Summary of target issues and mitigation strategies

Issues	Tools
Hydrodynamic stability	Adiabat shaping: Relaxation pulses, decaying shocks (laser pickets) Thin High-Z cover layers Low density foams Increase pellet adiabat Small laser wavelength (more ablative stabilization) Larger ignitors Target geometry (lower aspect ratio)
Symmetry	Larger ignitors Target geometry (lower aspect ratio)
Coupling/LPI	Minimize laser wavelength High laser bandwidth Ablator composition Compression/ignitor energy trade-off Target geometry (higher aspect ratio)

LPI during the compression pulse?

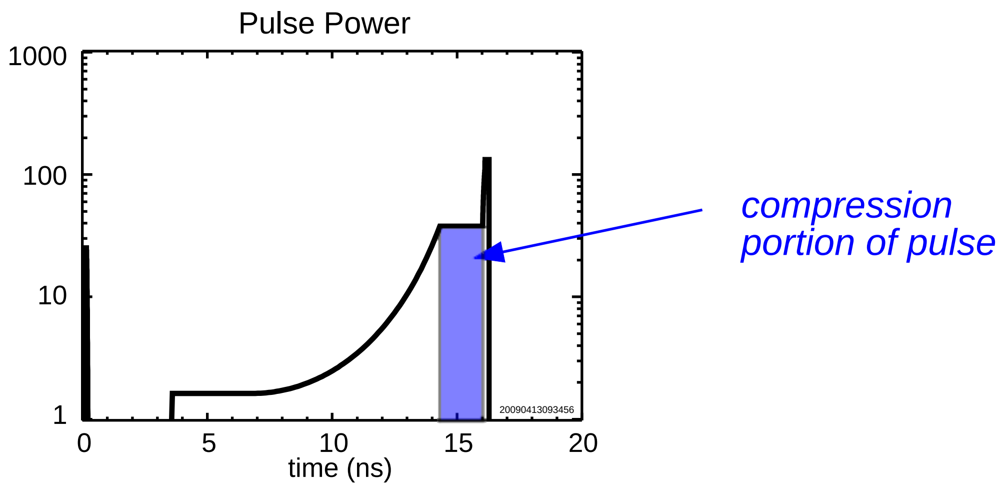
Fast electrons can preheat the fuel and prevent compression.

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).*

To date, two plasmon decay experimental data shows that simple formula seems to predict threshold

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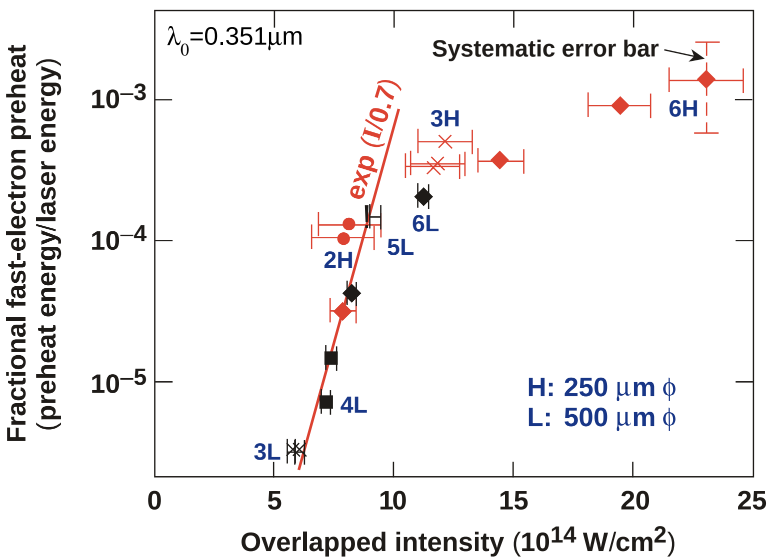
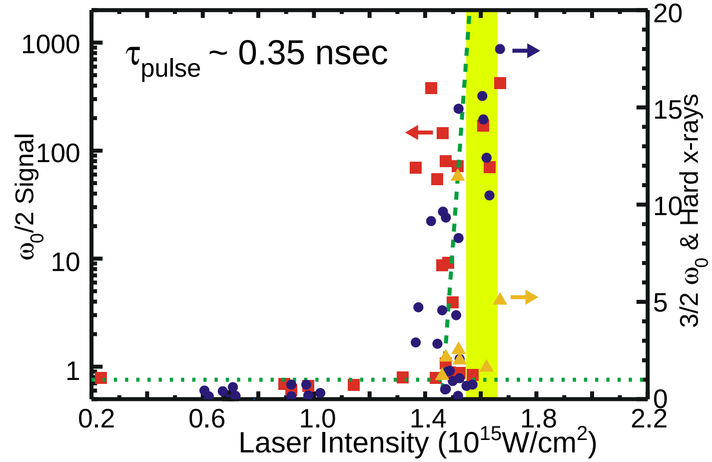
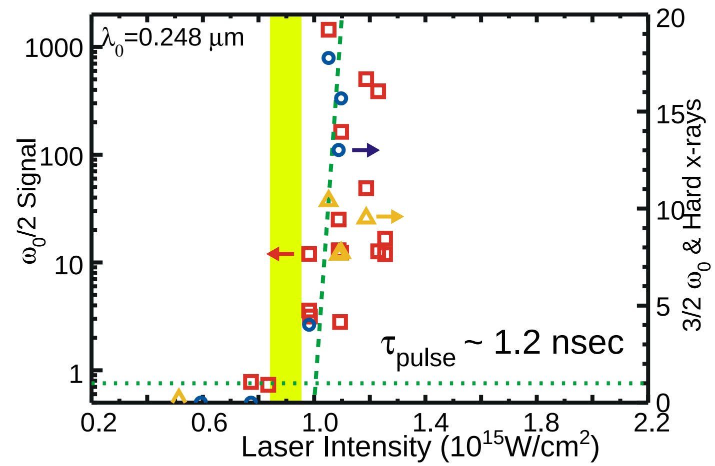
Omega experiments show $2\omega_{pe}$ near simple threshold



Stoeckl, et al., Phys. Rev. Lett. ***90*** *235002 (2003), and Anomalous Absorption Conf. 2003*

Nike experiments *(J. Weaver et al.)* also show $2\omega_{pe}$ near simple threshold





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

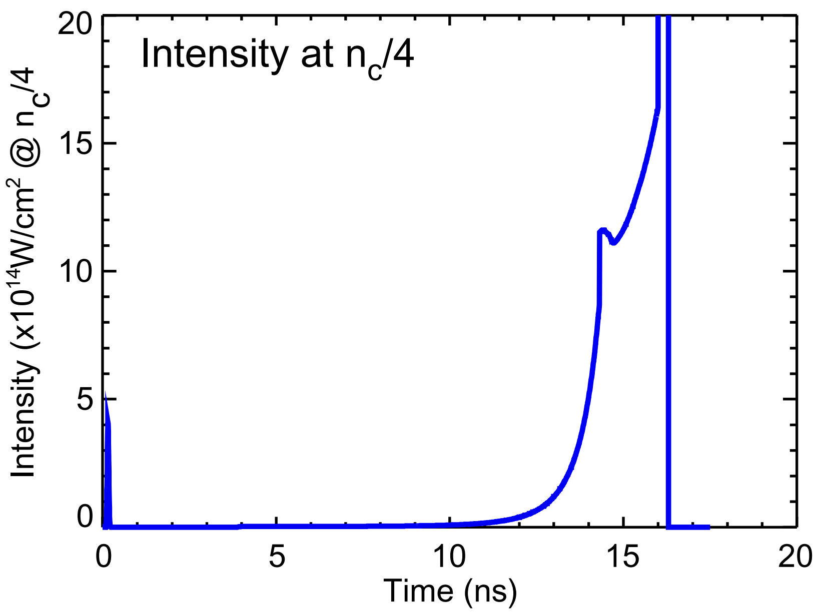
Unresolved:

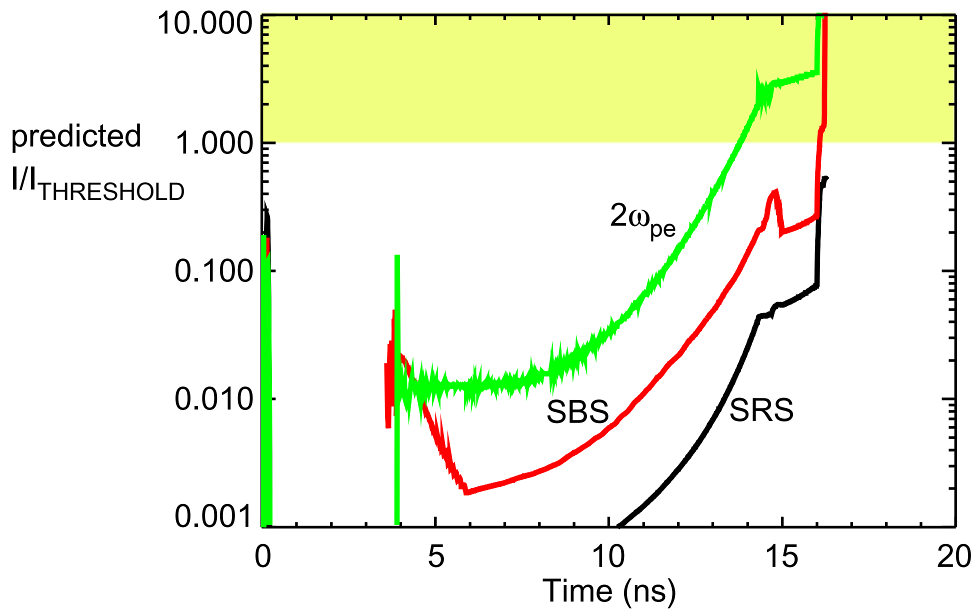
Will simple formula continue to hold?

If over threshold, will LPI harm gain?

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

baseline ~ 500 kJ shock ignition target





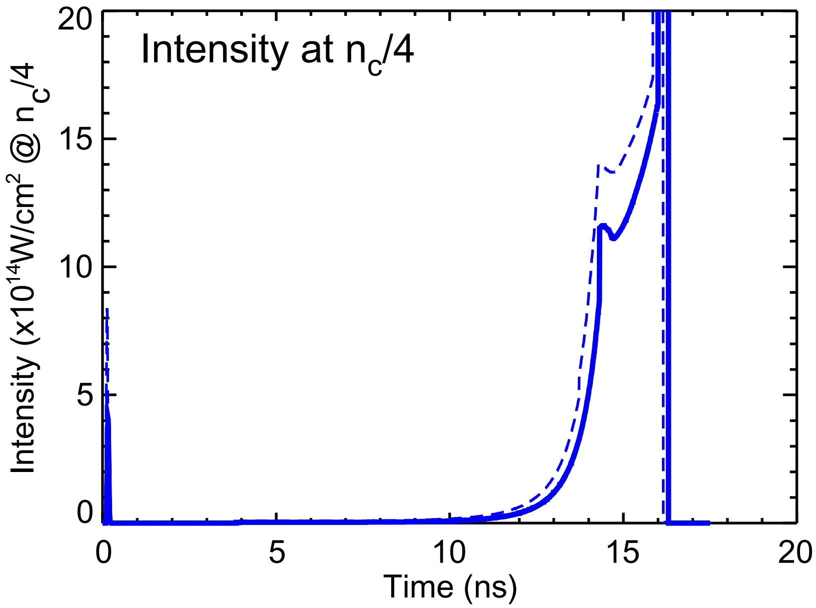
predicted $I/I_{2\omega pe\text{-}threshold}$

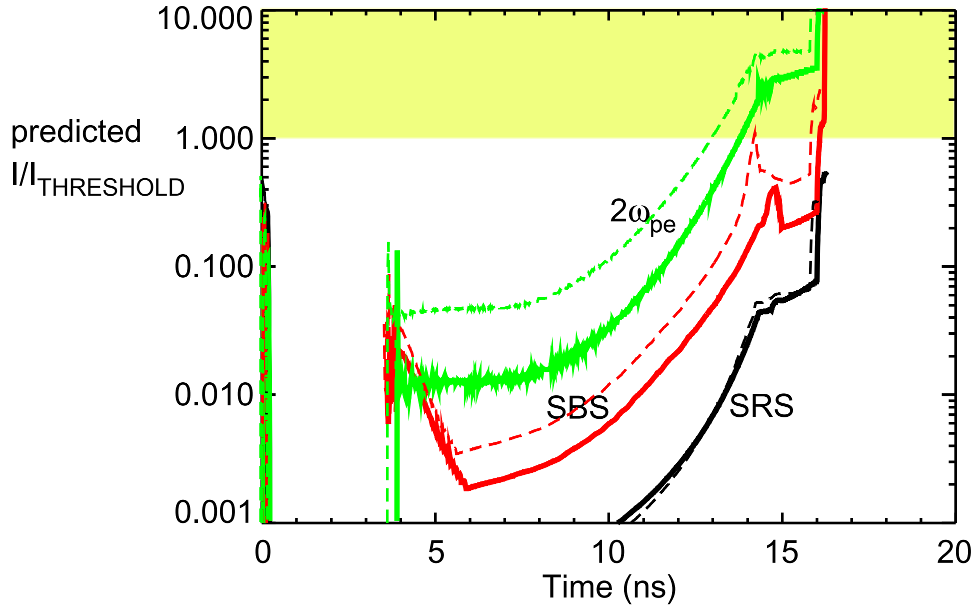
$$I_{15} \sim 80 \frac{T_{kev}}{\lambda_{\mu m} L_{d,\mu m}}$$

based on plane EM wave linear
plasma ramp analysis

The baseline shock ignition target is further above $2\omega_{pe}$ threshold during compression for 0.351nm light.

baseline ~ 500 kJ shock ignition target





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

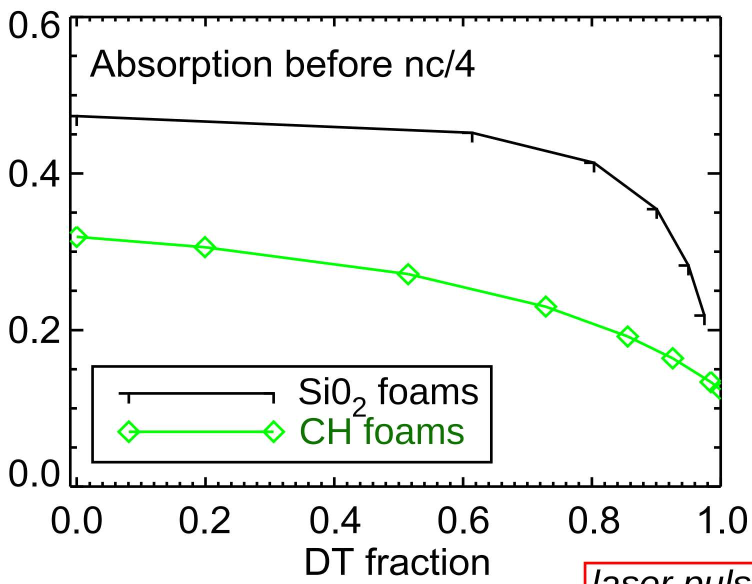
$$I_{15} \sim 80 \frac{T_{kev}}{\lambda_{\mu m} L_{d,\mu m}}$$

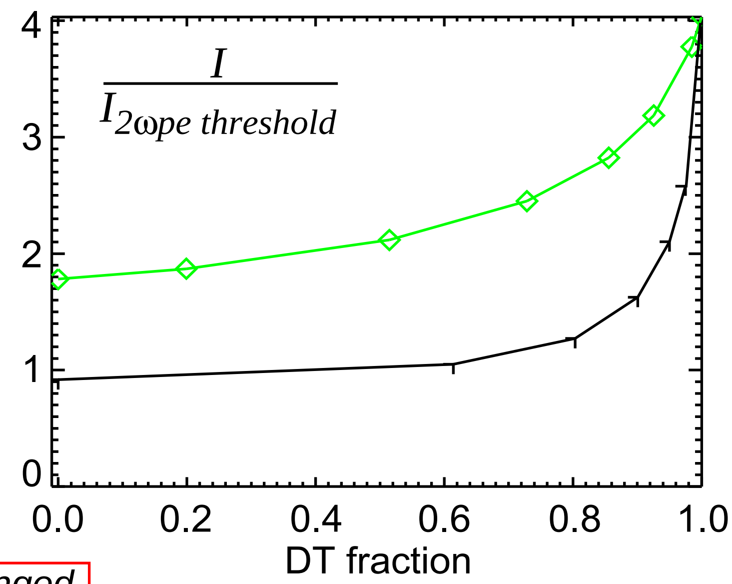
based on plane EM wave linear
plasma ramp analysis

Higher-Z DT/foam ablators: LPI is reduced but so is drive pressure

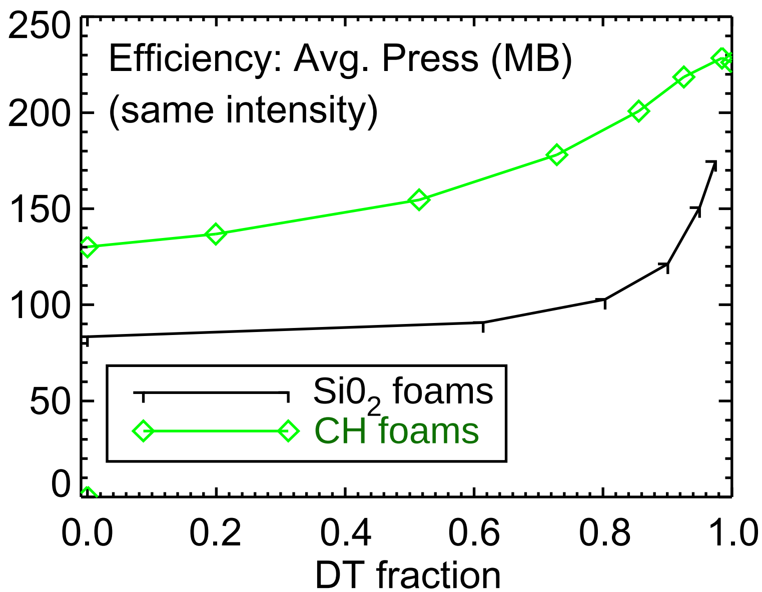
Ablators are formed from different density foams (50 mg/cc - solid) which are filled with DT and frozen. CH and SiO_2 foams are shown here.

(smaller DT fractions are more absorptive)





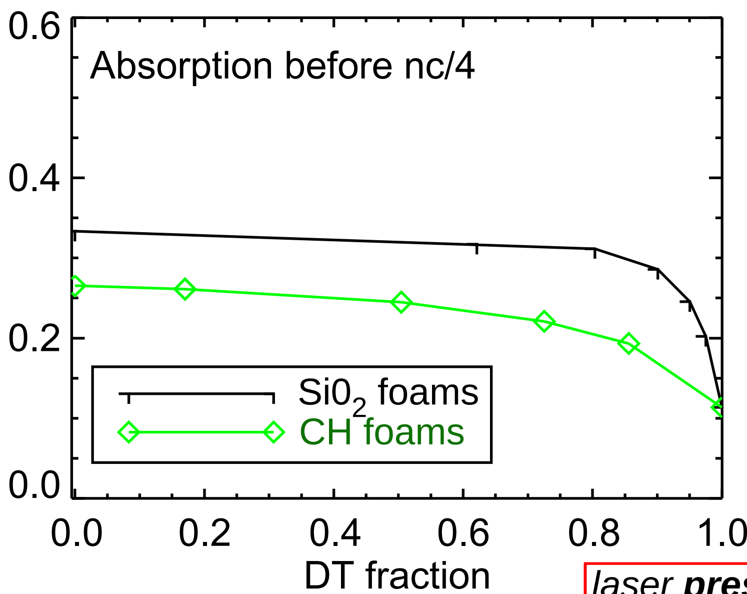
laser pulse is unchanged

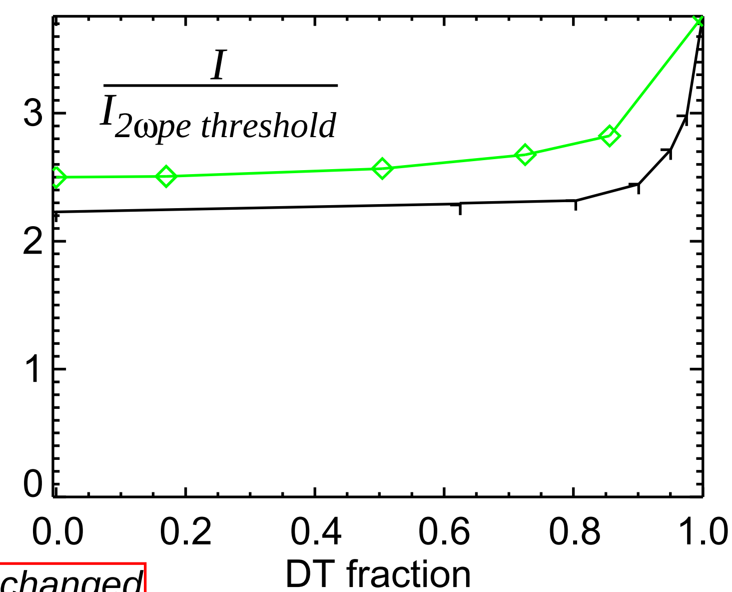


However, the increasing absorption moves the thermal front away from the ablation surface and helps to decrease the hydrodynamic efficiency (generated pressure)

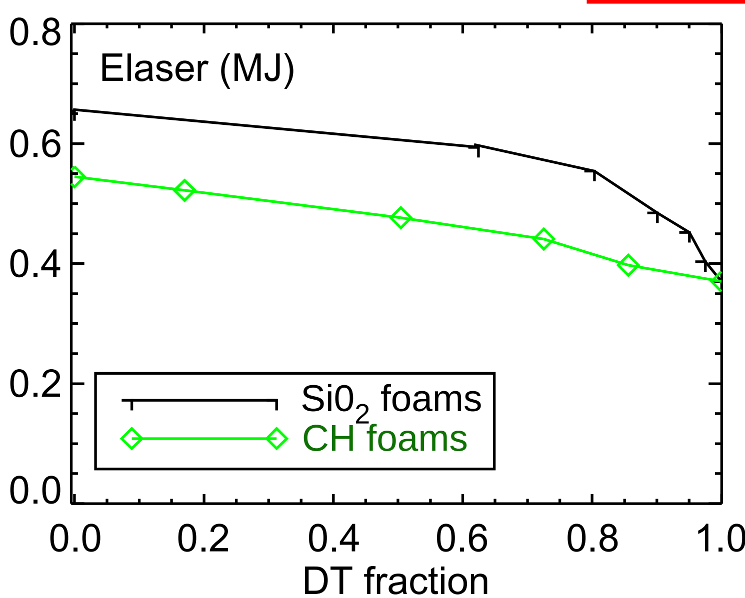
Higher-Z DT/foam ablators: constant drive pressure requires more energy & negates most LPI mitigation

If we change the laser pulse so that the ***drive pressure is constant***, more energy is needed and the change in LPI risk is minimal





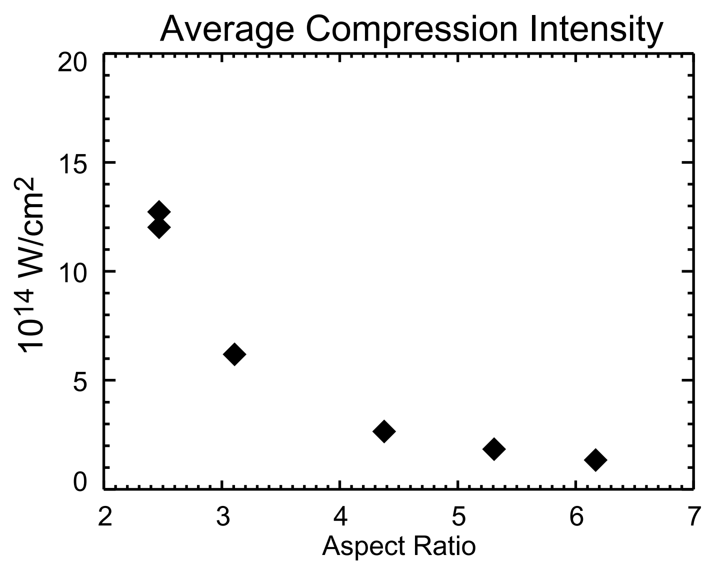
*laser **pressure** is unchanged*

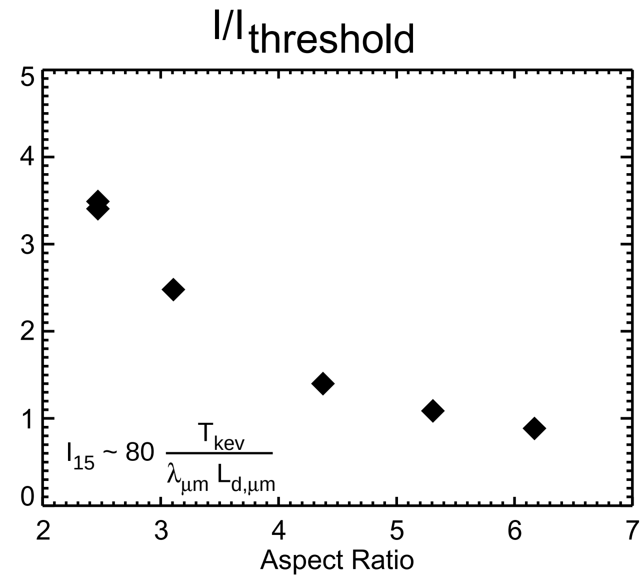


At constant drive pressure, higher-Z ablators require more energy and reduce LPI risk only slightly.

Conclusion:
There is little or no advantage in increasing the collisionality of the ablator

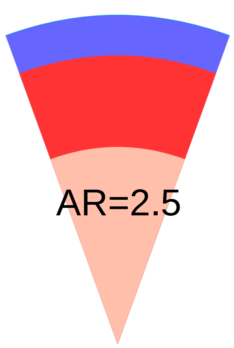
Increasing the initial Aspect Ratio (AR) allows one to use lower drive intensities and decrease LPI risk

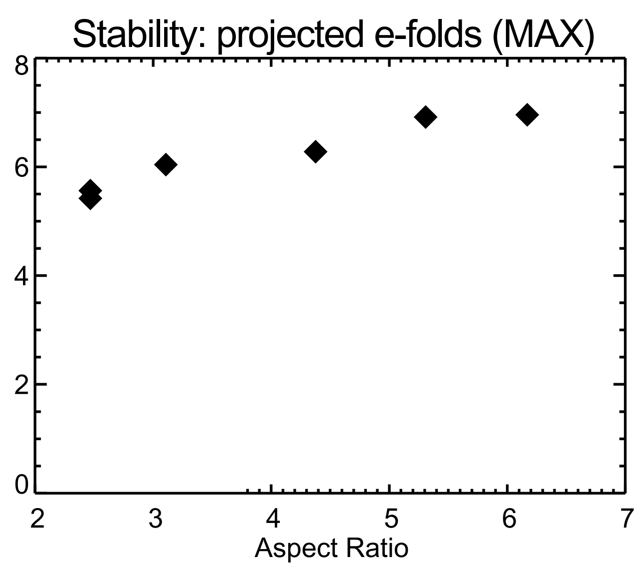


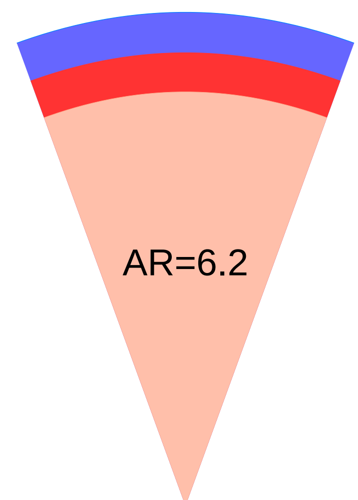


... but stability is worse

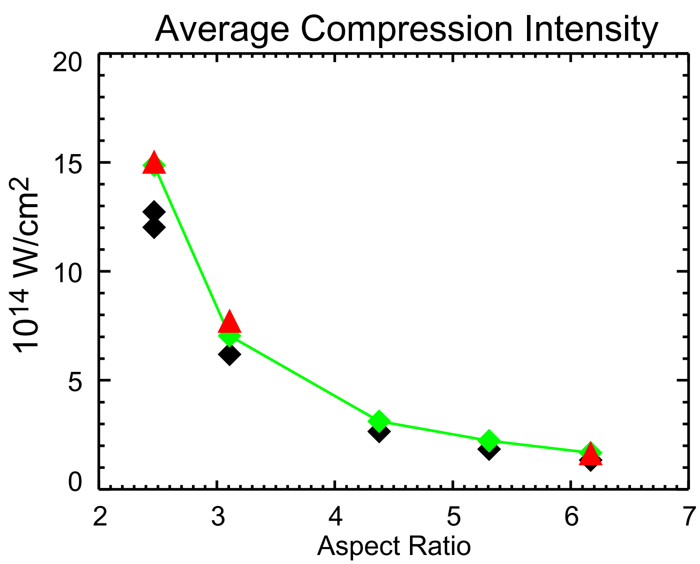
$$AR = \frac{R_{outer} - R_{inner}}{R_{outer}}$$

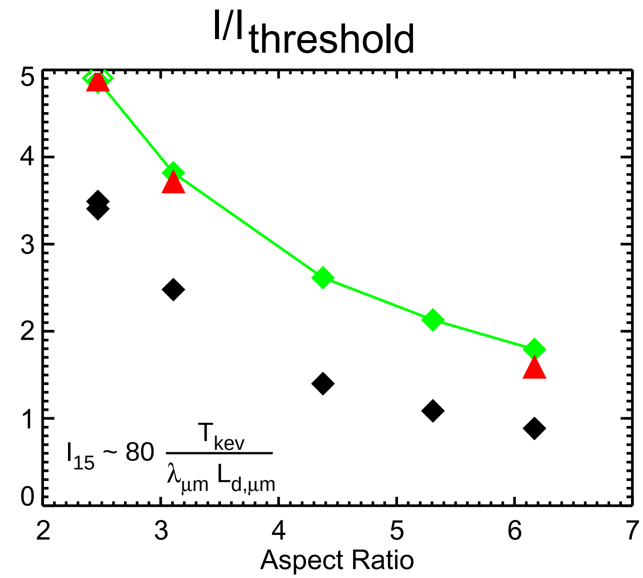






Increasing the initial Aspect Ratio (AR) : the problem is significantly worse with 351 nm light





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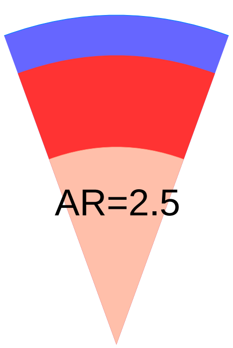
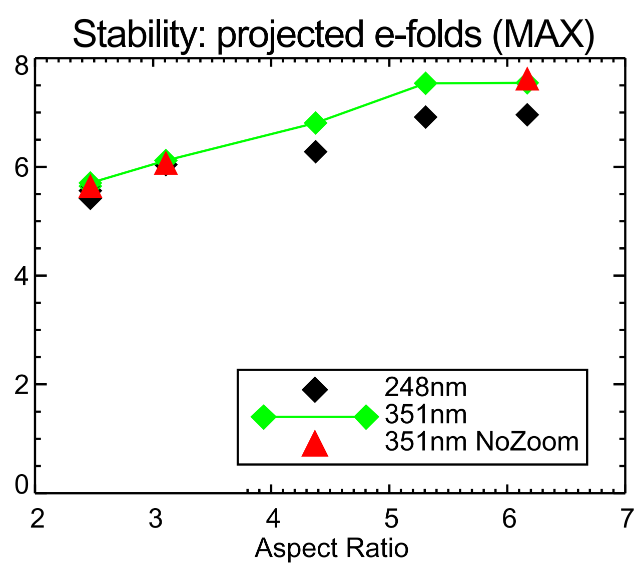
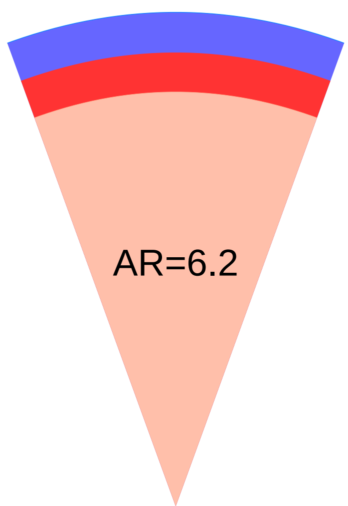
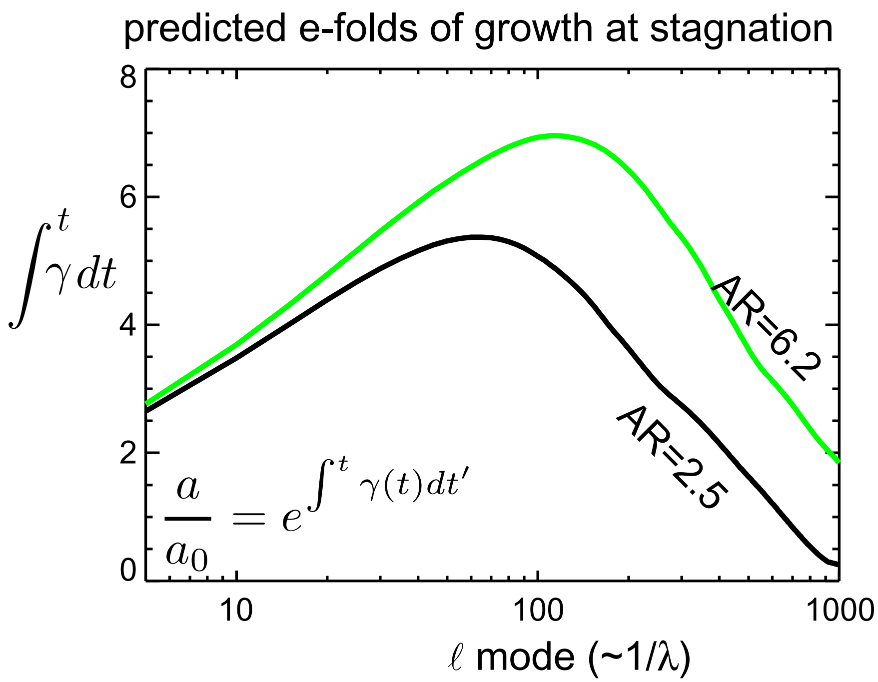
$$AR = \frac{R_{outer} - R_{inner}}{R_{outer}}$$





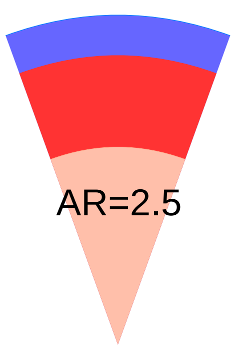


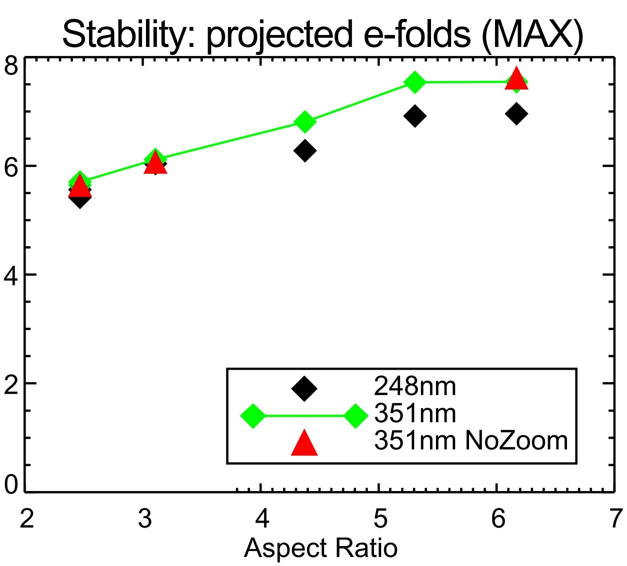
Increasing the initial Aspect Ratio (AR) gives higher-mode (small wavelength) instability in the target

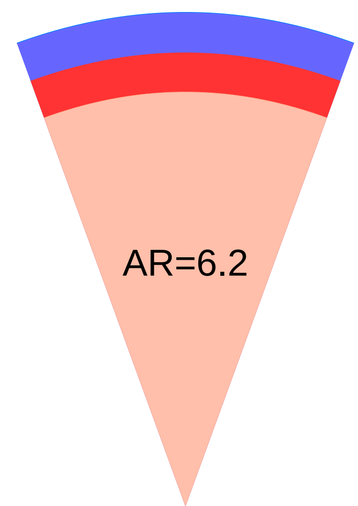


less ablative stabilization: more short-wavelength growth

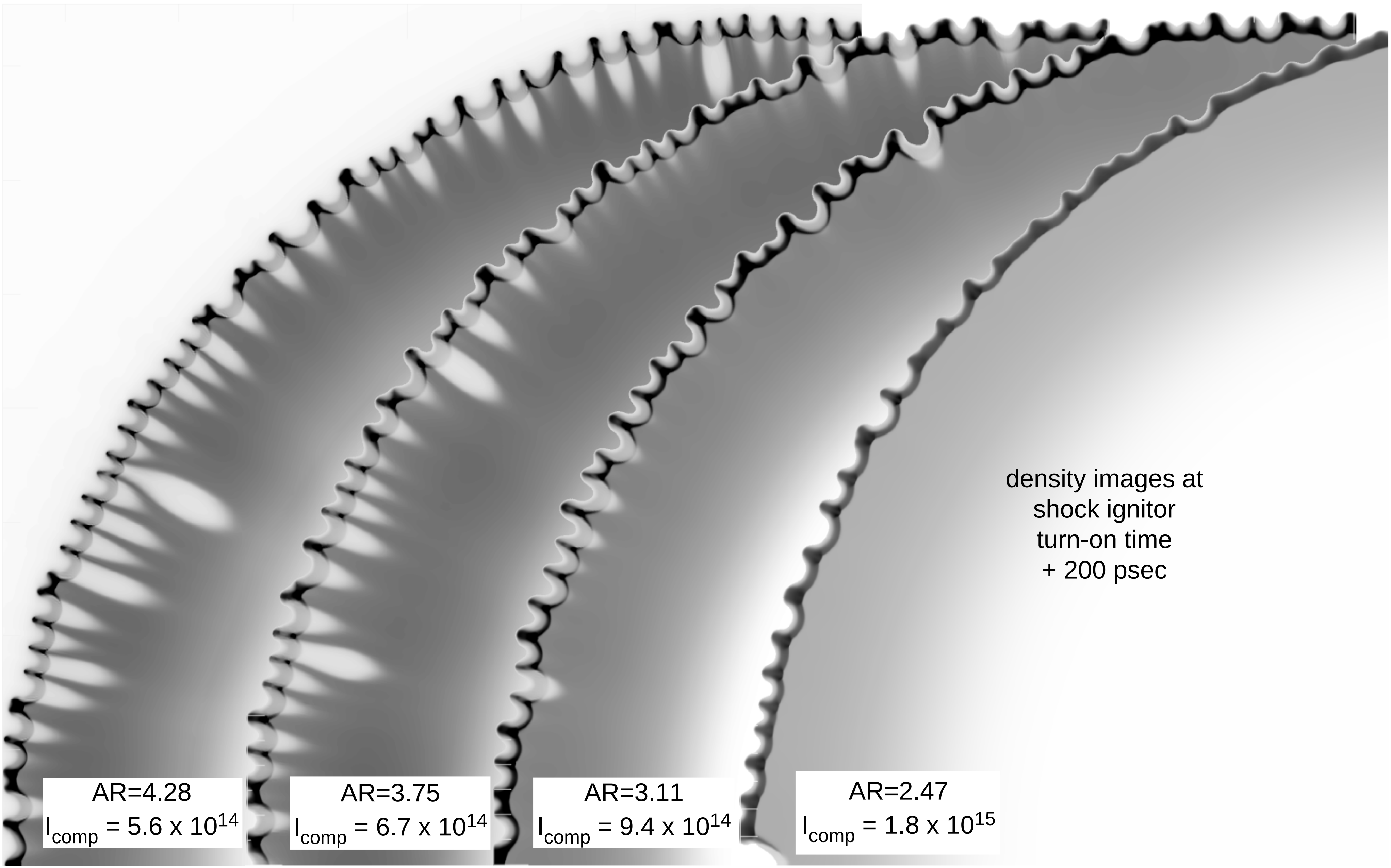
$$AR = \frac{R_{outer} - R_{inner}}{R_{outer}}$$







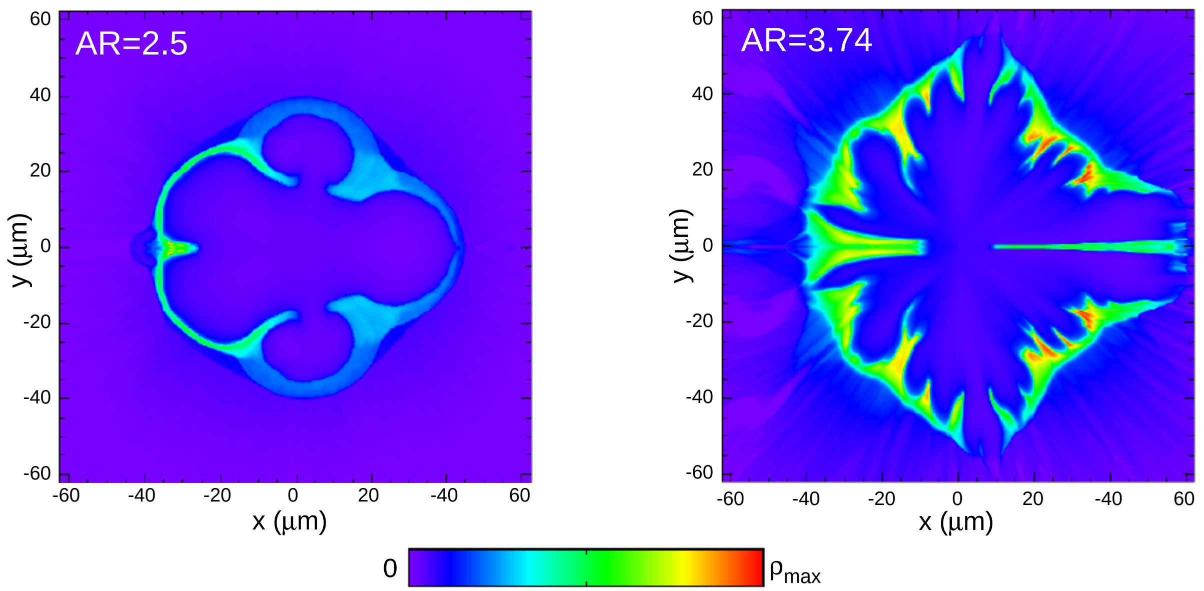
Effects of lower intensity: 2D simulations of higher aspect ratio (AR) targets show greater growth of RT



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

Higher aspect ratios are more distorted at ignition time and need more ignitor power

Example: AR=2.5 (baseline) vs. AR=3.74



AR:	2.5	3.74
Max. $I_{compress}$	2.5×10^{15}	6.8×10^{14}
Ignitor power 1D: 2D:	 70kJ 130kJ	 57kJ 225kJ
Gain: 1D: 2D:	 143 124	 187 110

% aR=2.5 pic: 20090921141850 : 04Oct2009_01 : 16.95 ns
% ar-3.7 pic: 20091116133641 : 13Nov2009_02 : 16.66 ns

Summary

We've designed a variety of shock ignition targets.

The performance of these target is predicted to be good if nominal constraints on surface finish, optical smoothing are obeyed.

More energy in the ignitor pulse cures most problems.

One of the biggest unknowns in the designs are due to laser plasma instabilities. LPI will determine the maximum allowed drive intensity during compression.

-> the pellet aspect ratio

-> hydrodynamic stability

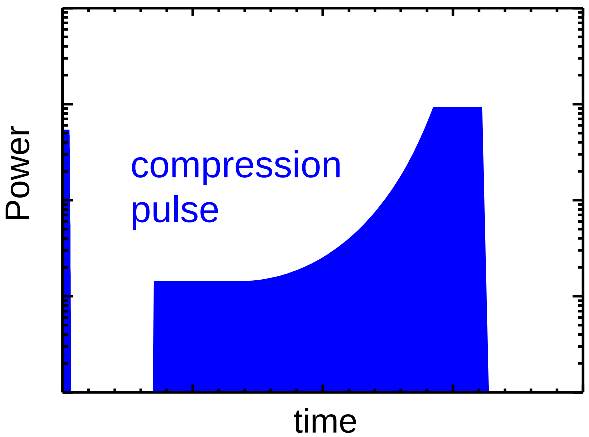
Absorption physics (nonclassical) during the ignitor shock is also uncertain
and may be important.

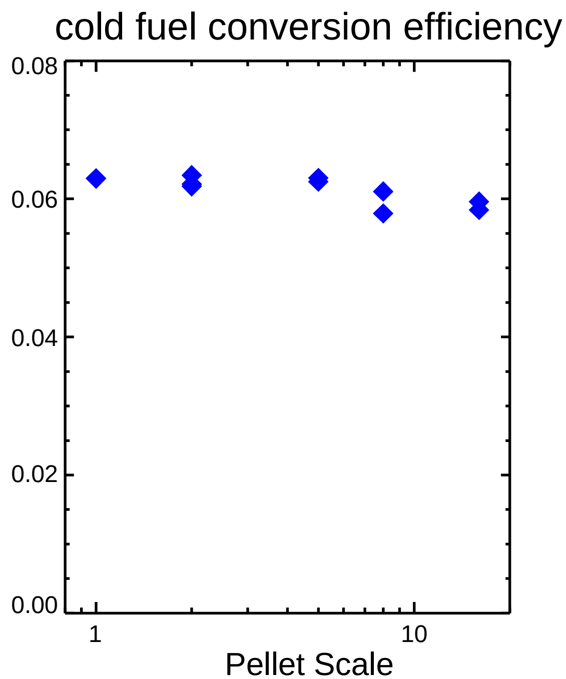
backup slides

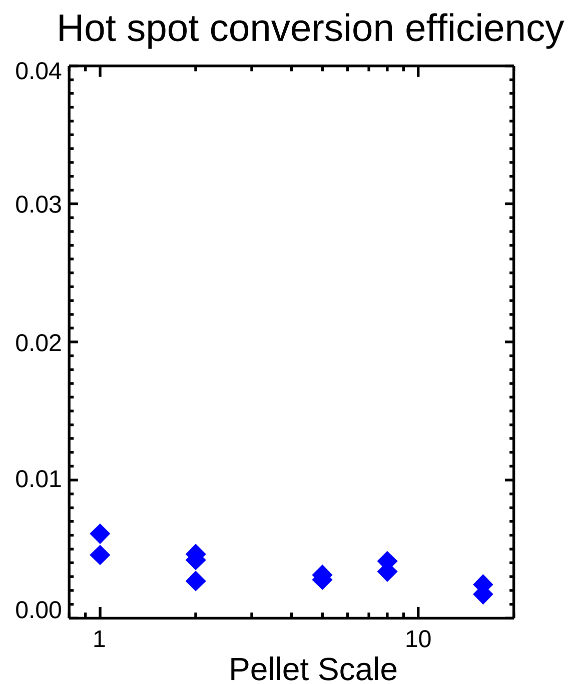
How efficient are we in assembling the fuel?

The pulse efficiencies can be calculated from the simulations
- measure hot spot and cold fuel energy at ignition time
- use a pulse without an ignitor spike

Conversion efficiency for the compression pulse is relatively low because of the low implosion velocities







$$\eta \sim I^{-0.29} V_{imp}^{0.87} \lambda^{-0.58}$$

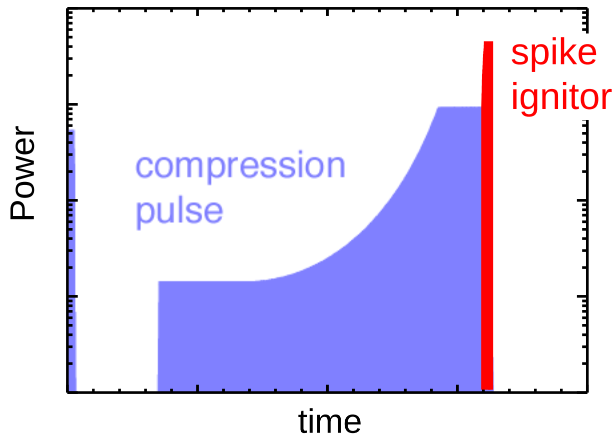
$$\text{conversion efficiency} = \frac{\text{assembled fuel internal energy}}{\text{absorbed laser energy}}$$

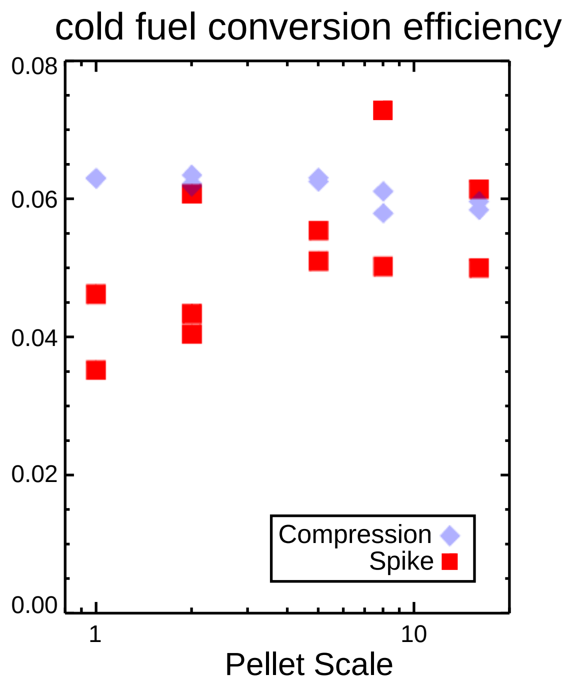
*C.D. Zhou and R. Betti, Phys. Plasmas **14,** 072703 (2007)*

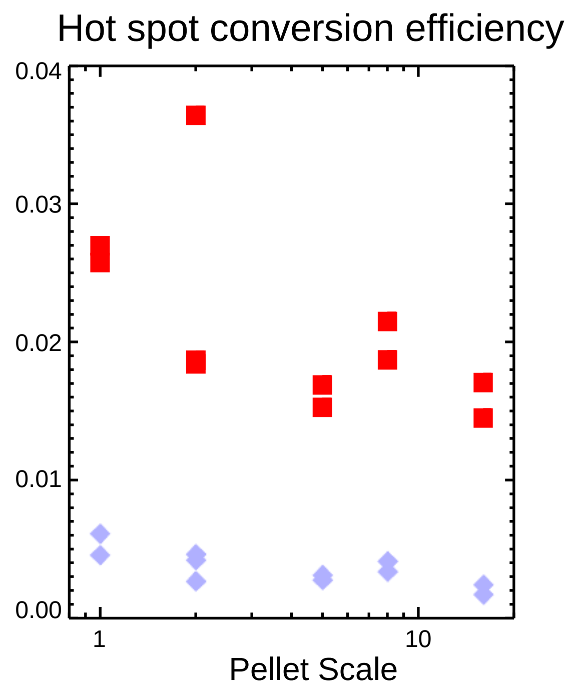
How efficient are we in assembling the fuel?

The pulse efficiencies can be calculated from the simulations
-- measure hot spot and cold fuel energy at ignition time
-- use a pulse with an ignitor spike

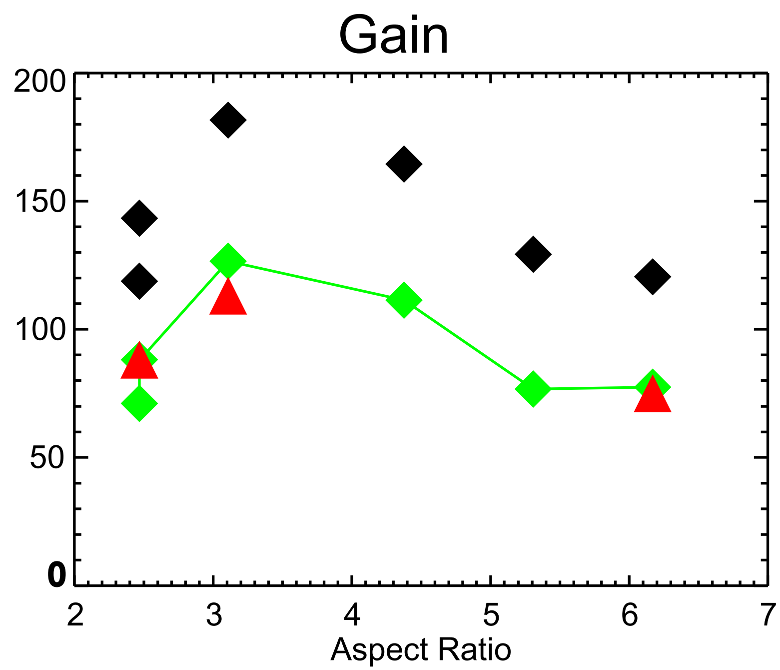
Hot spot conversion efficiency for the spike ignitor pulse, though small, is much higher than for compression pulse.







$$\text{conversion efficiency} = \frac{\text{assembled fuel internal energy}}{\text{absorbed laser energy}}$$


Gain
200
150
100
50
0
2
3
4
5
6
7
Aspect Ratio

What could possibly go wrong?

These 2D target simulations did not include beam power imbalance, beam mispointing or target displacement (ℓ=0)

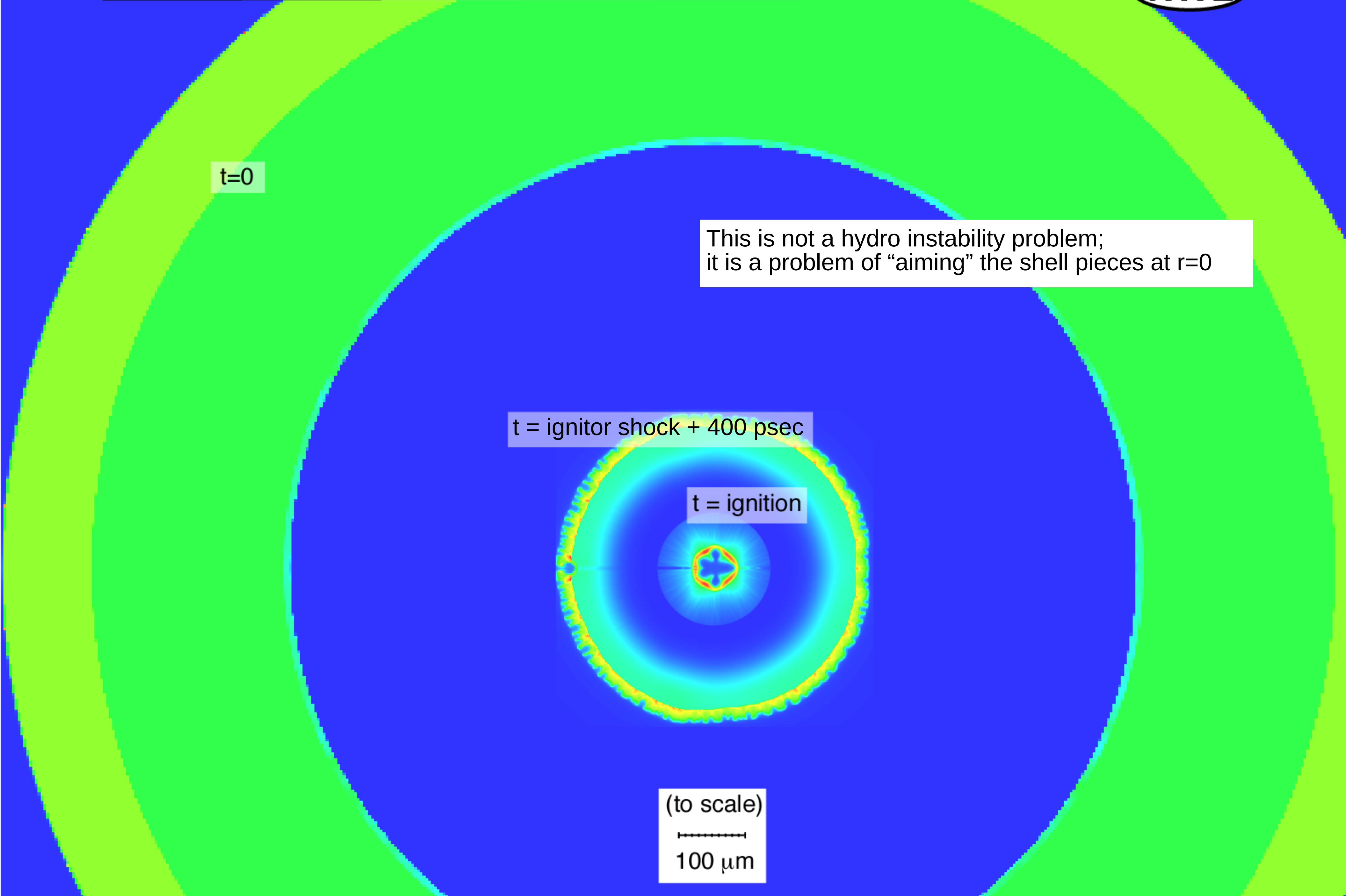
Convergence Ratio (CR) is high for these targets -- more sensitive to large wavelength perturbations (such as those above)

LPI may limit intensity to values below those assumed here
- solved by increasing target size -> more hydro-instability

Nonlocal electron transport an issue?

An important constraint for shock ignition is the high convergence ratio

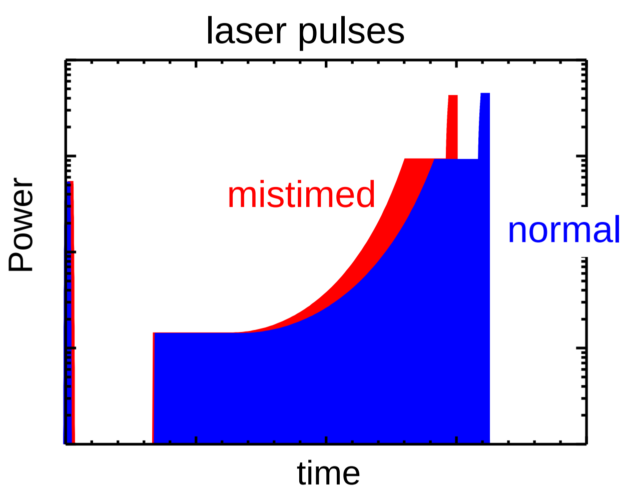
This is not a hydro instability problem;
it is a problem of “aiming” the shell pieces at r=0

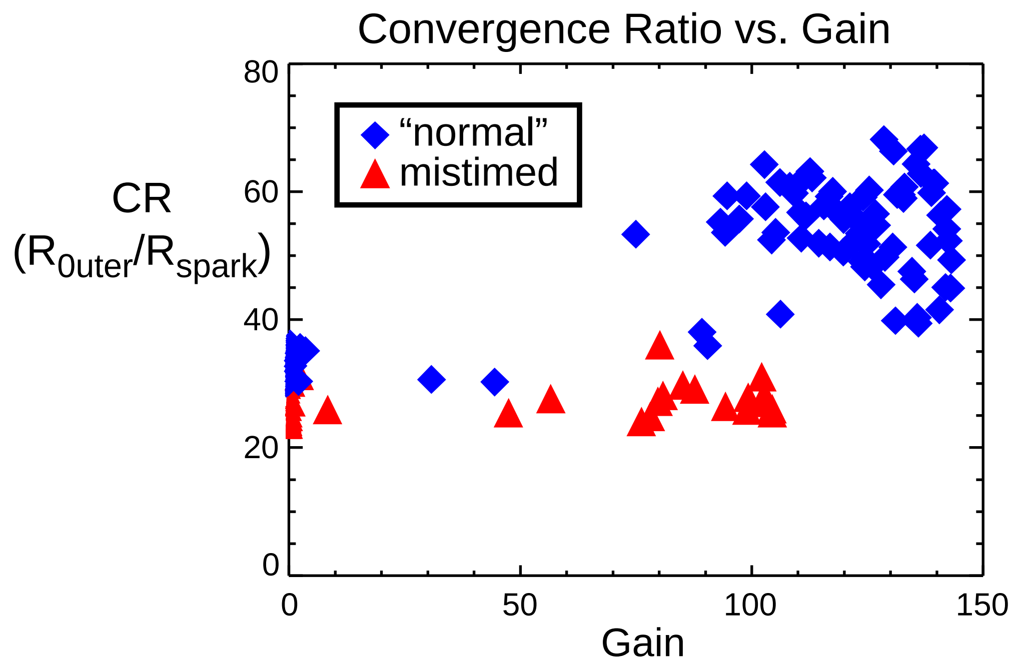


How can we compensate for high convergence ratio?

1. More spike power

2. Design for larger convergence ratio:
   To make a larger hotspot, mistime the main pulse (by ~ -1.2 nsec)
   - the main shock overtakes the foot shock prior to shock breakout.
   - more inner edge of fuel shell joins hotspot, making it larger.

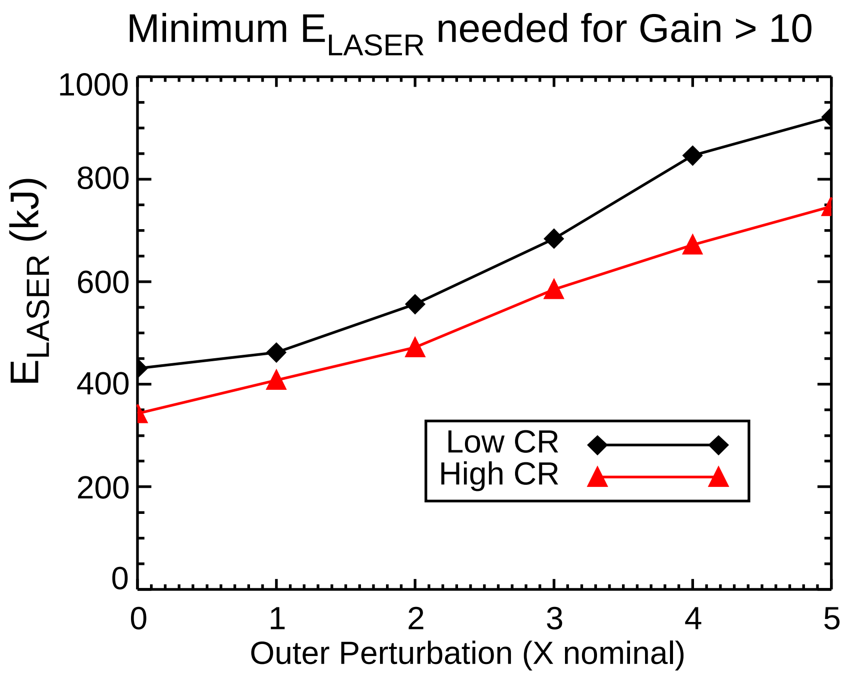


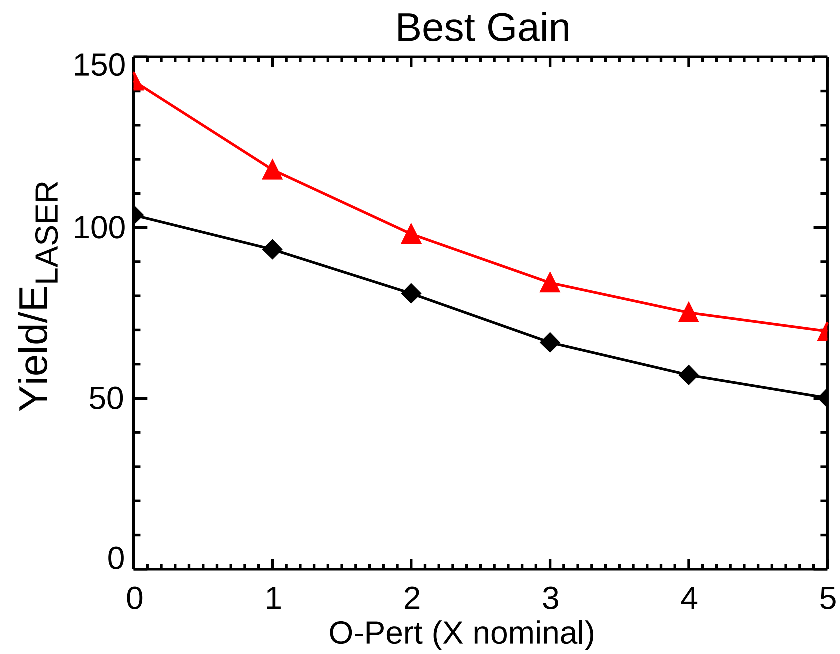


Creating a larger hot spot by mistiming reduces the convergence ratio but also reduces the gain.

2D simulations do not support designing for lower CR via mistiming

(results from many low-mode (ℓ=1-8, 64 pt) simulations)





As perturbation increases, more laser energy (in spike) is needed.
However, the lower CR does not decrease the sensitivity.

For lower CR, the resulting gains are lower
-- at ALL asymmetry levels

Best option to handle low mode asymmetry: increase spike energy

TIME:Wed Jun 3 10:08:00 2009

Mitigation strategies for LPI during the compression pulse?

The impact of LPI will depend upon number and energy of hot electrons generated, which is still quite unknown. However, the drive intensity during compression may have to be lowered if LPI proves problematic.

How can we lower the drive intensities?
Three possibilities are investigated here:

1. Use as short a laser wavelength as possible.
   ($I_{threshold} \sim 1/\lambda_0$)

2. Increase absorption (higher Z ablators) to limit intensity at $n_c/4$.

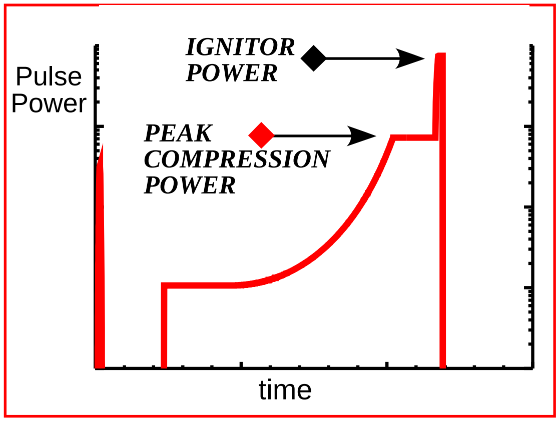
   Smalyuk et al., Phys. Rev. Lett. ***104****, 165002 (2010).*

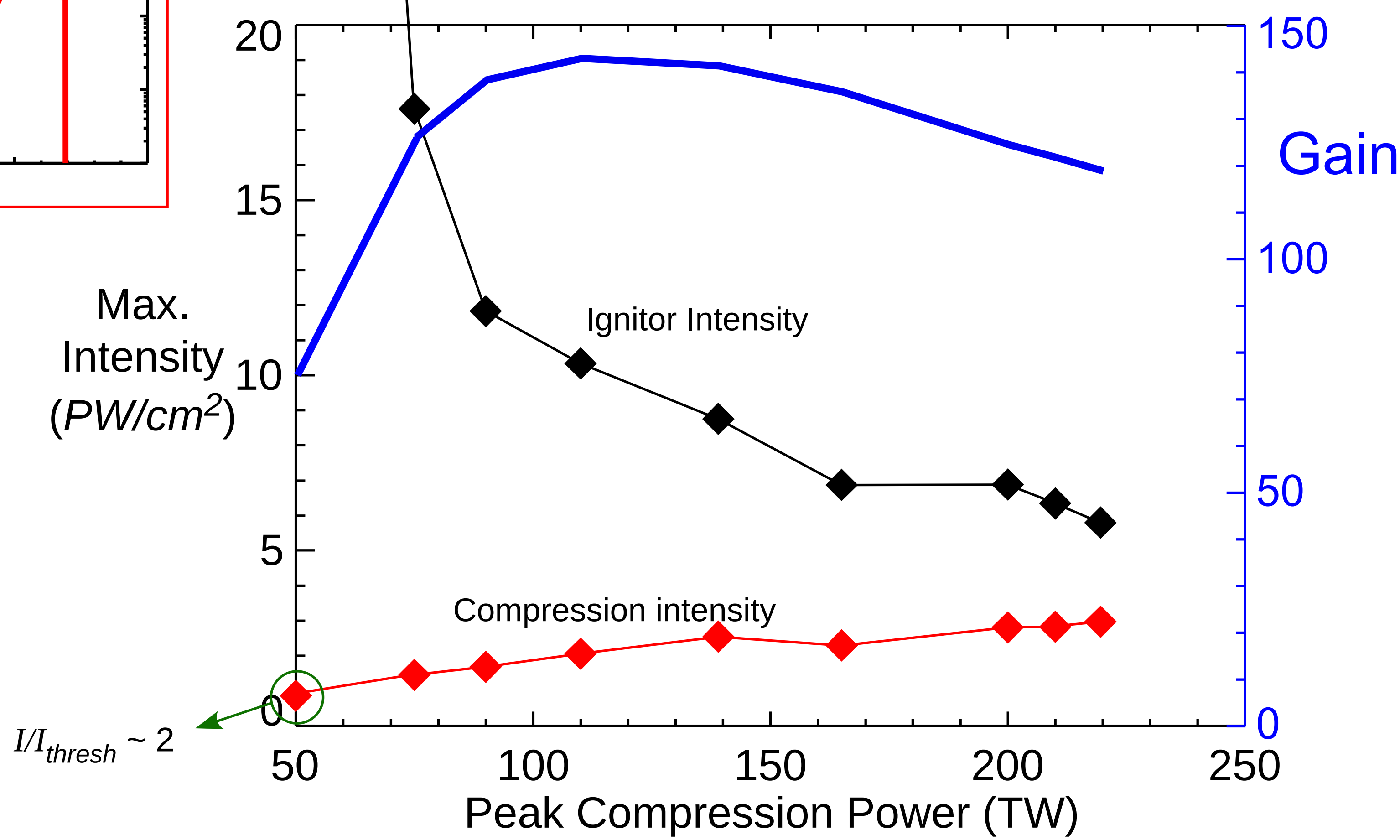
3. Redesign the target for lower intensity / drive pressure.

   - lower compression intensity, larger ignitors

   - larger targets and higher initial aspect ratios

Another option to reduce intensity: use smaller compression power -- but a larger ignitor power



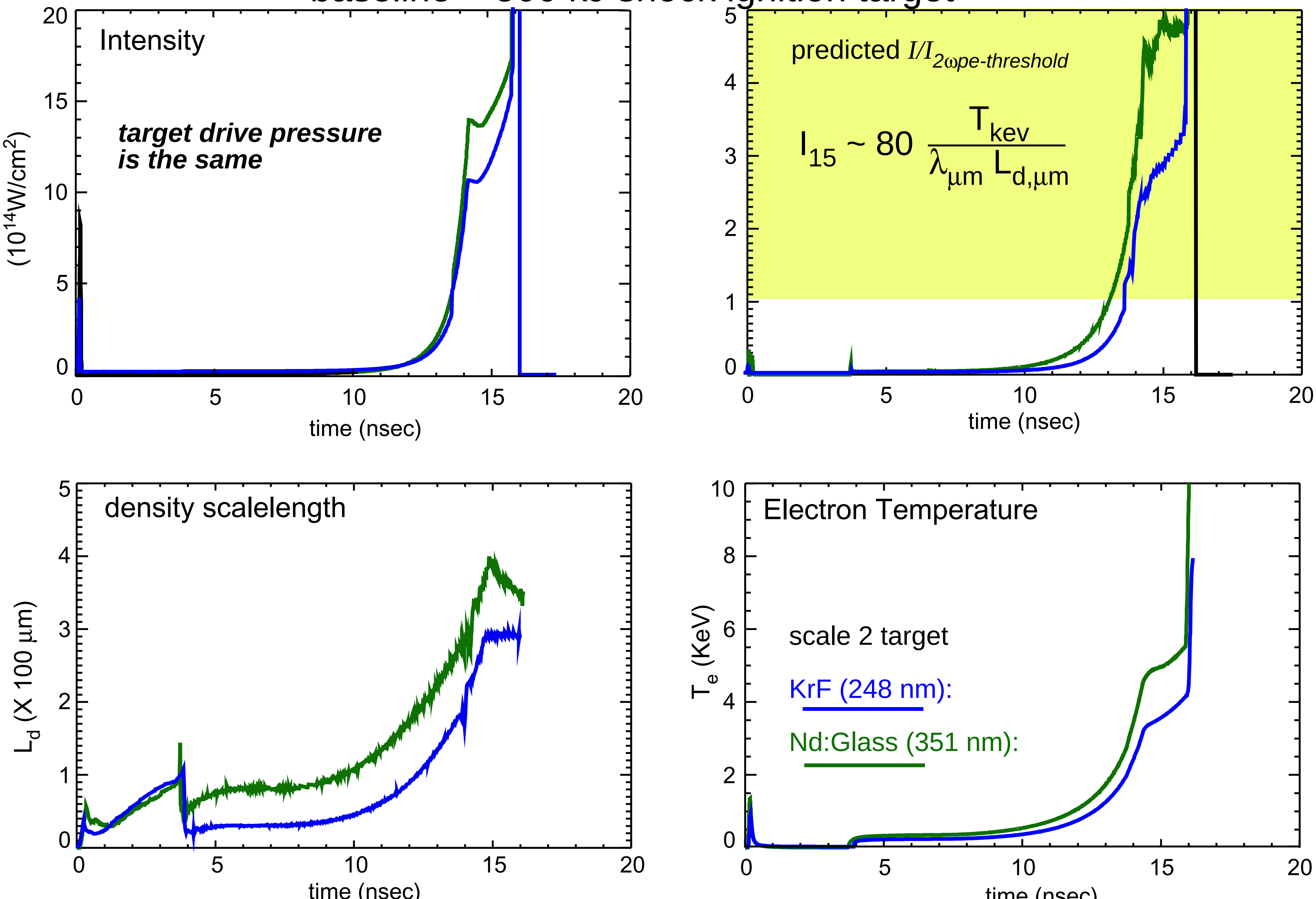


Problem: diminishing returns are quickly reached

Scale 2 target, E_{laser} ~ 400-500 kJ

Compared to KrF, frequency-tripled glass lasers will find it more difficult to stay below $2\omega_{pe}$ thresholds

baseline ~ 500 kJ shock ignition target



all quantities measured at $n_c/4$

getnc25_parms_1d WLAZ=0.351 um: 20101012131506 Wed Oct 13 11:29:10 2010
getnc25_parms_1d WLAZ=0.25 um: 20090226134930 Wed Oct 13 11:29:17 2010