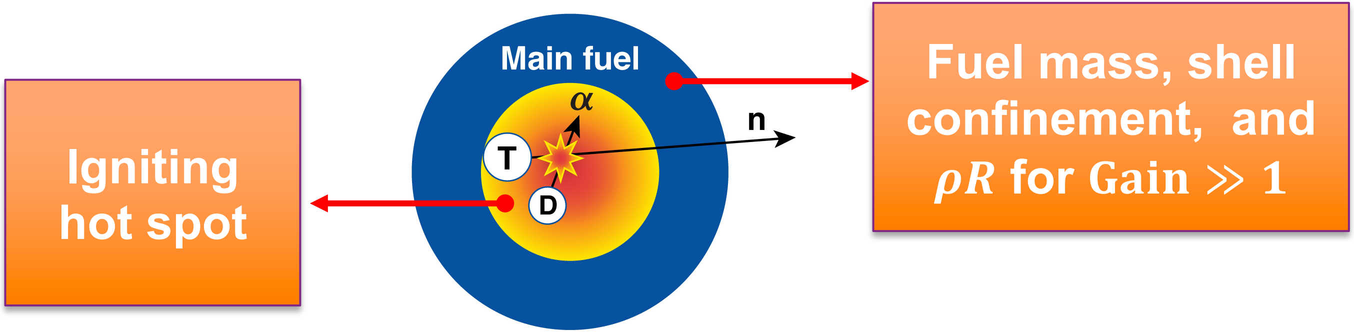
Physics Requirements for High-Gain Inertial Fusion Target Designs



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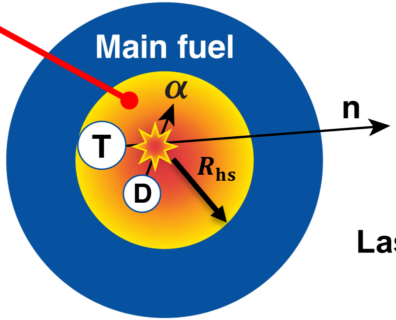
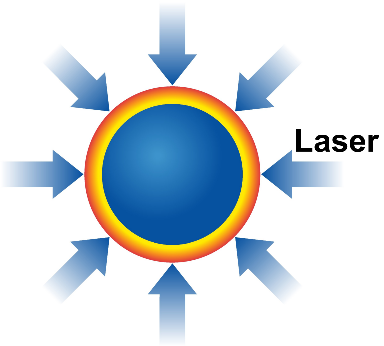
High-yield designs require igniting hot spot and shell confinement for burn wave propagation

Igniting hot spot





Ignition parameter

$$P_{hs}R_{hs} > 1\ \text{Gbar} \times \text{cm},\ T_i > 4.5\ \text{keV}$$

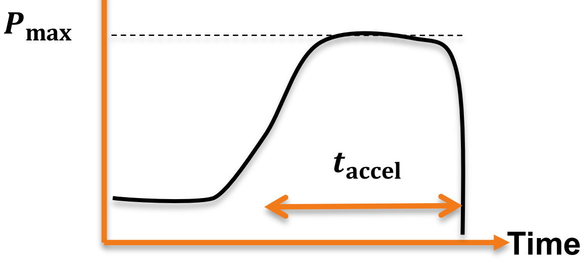
Scaling with implosion parameters:

$$P_{hs}R_{hs} \sim v_{imp}^3 \left(\frac{E_L}{I}\right)^{1/3} \frac{p_a^{4/15}}{\alpha^{4/5}} > (PR)_{min}$$

$$\text{Min}\,(v_{imp}) \sim \left(\frac{\alpha^{12/5}}{p_a^{4/5}} \frac{I}{E_L}\right)^{1/9}$$

Laser power

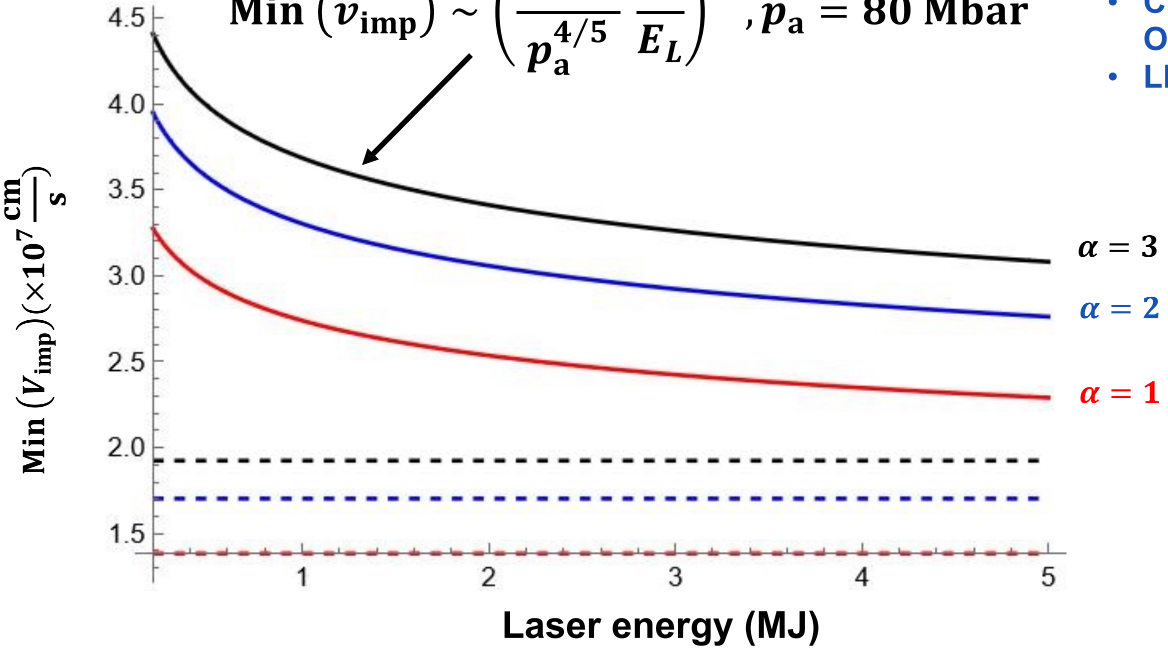
$$E_{laser} \simeq P_{max} t_{accel} \qquad I \sim \frac{P_{max}}{R^2}$$



The minimum implosion velocity required to create an igniting hot spot scales with ablation pressure, fuel adiabat, and laser energy

LDD implosions

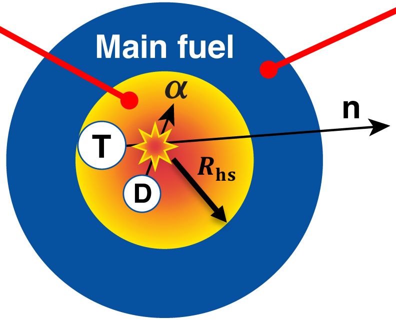
$$\mathrm{Min}\left(v_{\mathrm{imp}}\right) \sim \left(\frac{\alpha^{12/5}}{p_{\mathrm{a}}^{4/5}} \frac{I}{E_L}\right)^{\frac{1}{9}}, p_{\mathrm{a}} = 80\ \mathrm{Mbar}$$



- Current ablation pressures on OMEGA: $p_{\mathrm{a}} \sim 140$ MBar
- LDD NIF experiments: $p_{\mathrm{a}} \sim 80$ MBar

High-yield designs require igniting hot spot and shell confinement for burn wave propagation

Igniting hot spot



Fuel mass, shell confinement, and ρR for Gain ≫ 1

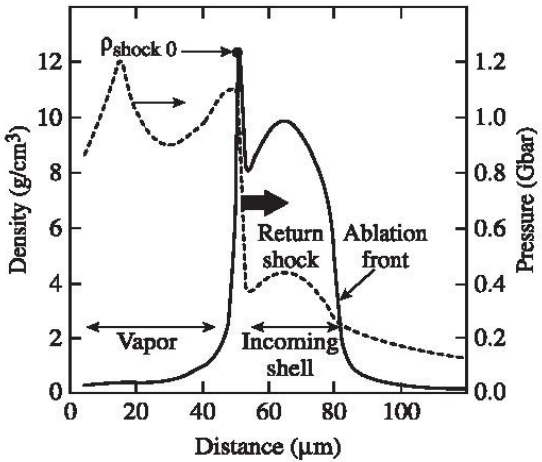
Ignition parameter

Scaling with implosion parameters:

$$P_{hs}R_{hs} \sim v_{imp}^3 \left(\frac{E_L}{I}\right)^{1/3} \frac{p_a^{4/15}}{\alpha^{4/5}} > (PR)_{min}$$

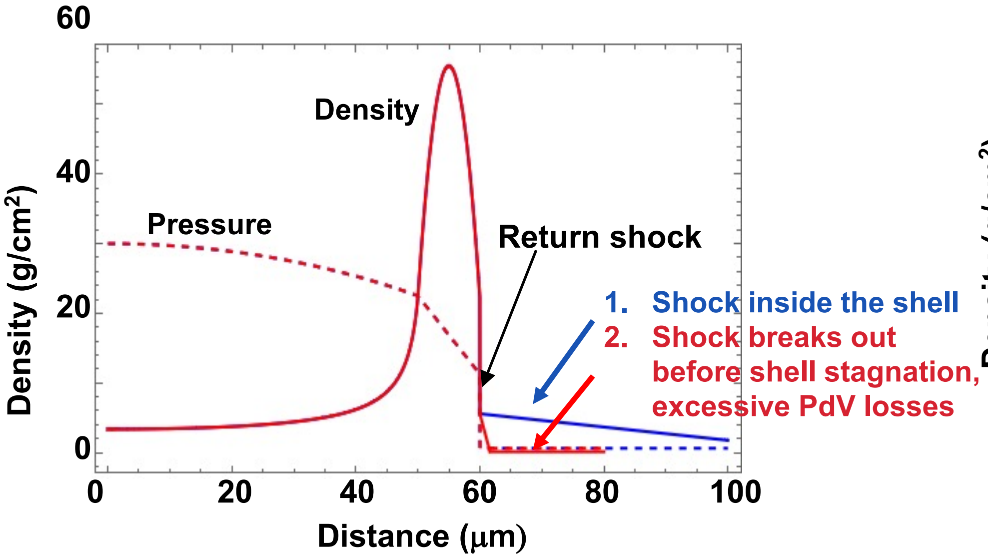
$$\mathrm{Min}\,(v_{imp}) \sim \left(\frac{\alpha^{12/5}}{p_a^{4/5}} \frac{I}{E_L}\right)^{1/9}$$

Shell confinement is limited to return shock propagation time

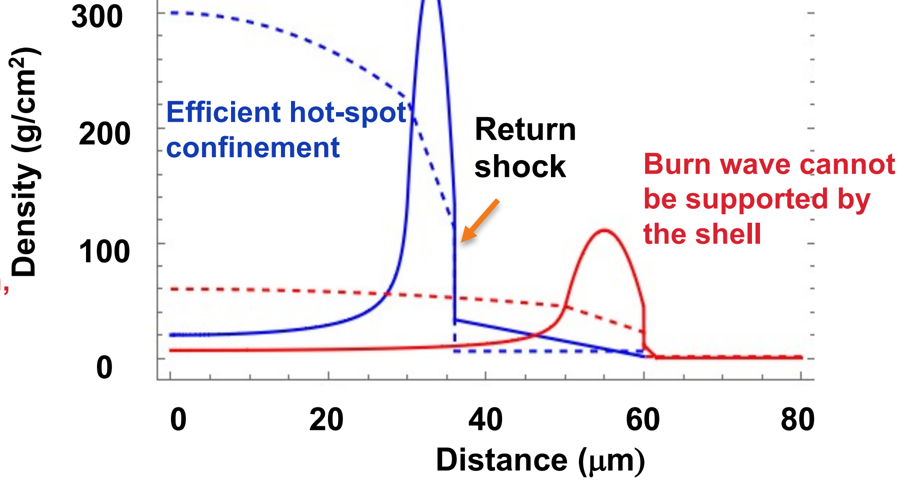


Shell confinement is limited to return shock propagation time

Two scenarios for shell and hot-spot compression:



Peak compression



To launch a burn wave into the main fuel, the return shock should not breakout of the shell prior to formation of an igniting hot spot; $M_{shocked}/M_{DT} \sim v_{imp}^{\frac{4}{3}} \alpha^{-\frac{2}{5}} p_a^{-\frac{13}{15}} < 1$

If the drive pressure is too low, the shell cannot provide the confinement required for burn propagation

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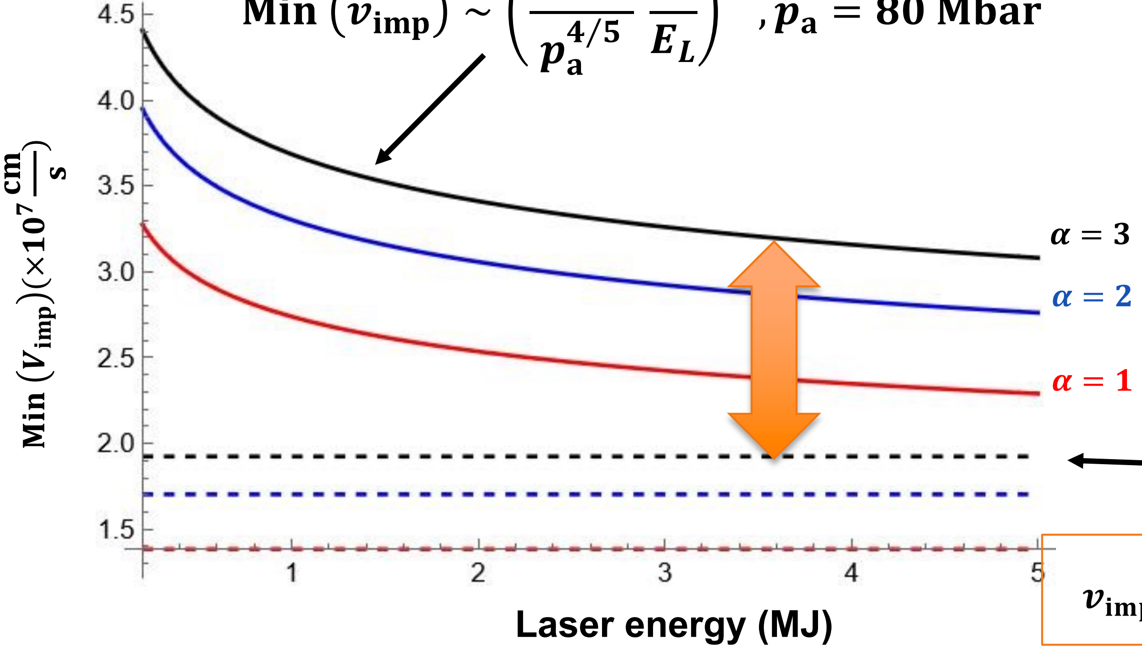
$$\mathrm{Min}\,(v_{\mathrm{imp}}) \sim \left(\frac{\alpha^{12/5}}{p_{\mathrm{a}}^{4/5}}\,\frac{I}{E_L}\right)^{\frac{1}{9}},\ p_{\mathrm{a}} = 80\ \mathrm{Mbar}$$



- Current ablation pressures on OMEGA: $p_{\mathrm{a}} \sim 140$ MBar
- LDD NIF experiments: $p_{\mathrm{a}} \sim 80$ MBar

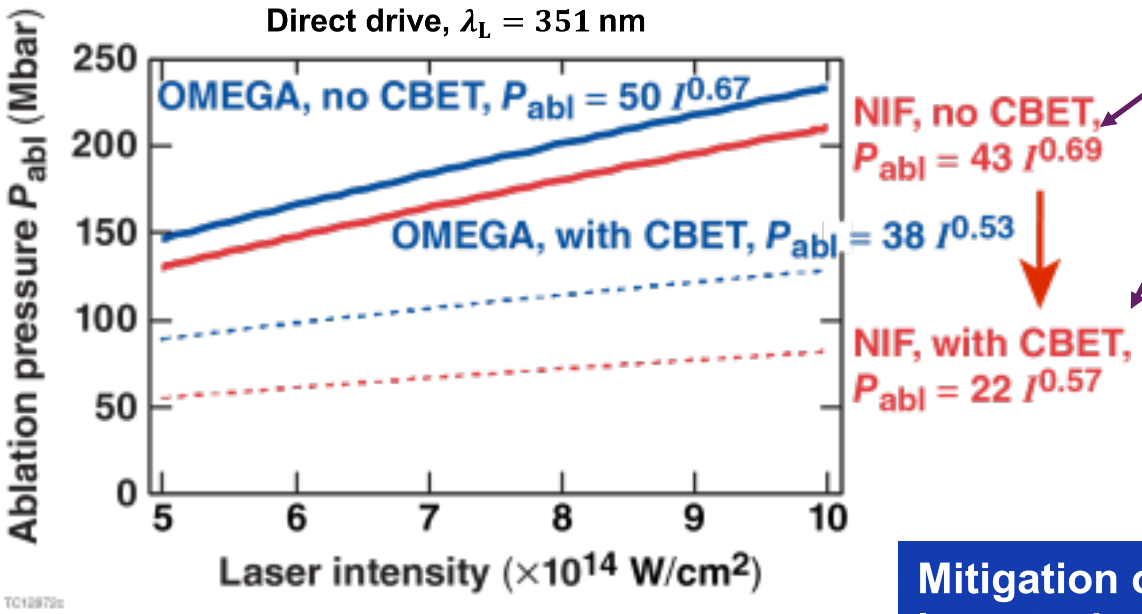
Hot-spot formation and shell confinement requirements do not overlap – no robust ignition is possible.

The limit on maximum velocity is set by shell confinement (shock inside the shell at ignition onset)

$$v_{\mathrm{imp}} < 1.6 \times 10^7\,\mathrm{cm/s}\ \alpha^{0.3}\left(\frac{p_{\mathrm{a}}}{100\ \mathrm{Mbar}}\right)^{0.65}$$

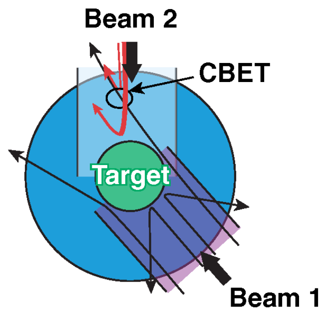
To realize the high-yield designs, ablation pressure must be increased.

Ablation pressure in current LDD experiments is limited by laser–plasma instabilities, mainly cross-beam energy transfer (CBET)



Bremsstrahlung absorption

Bremsstrahlung + CBET losses

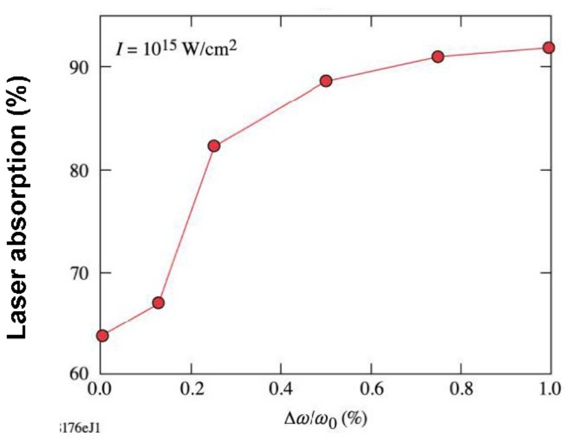


Mitigation of CBET losses using broadband laser technology is the main focus of the direct-drive program.

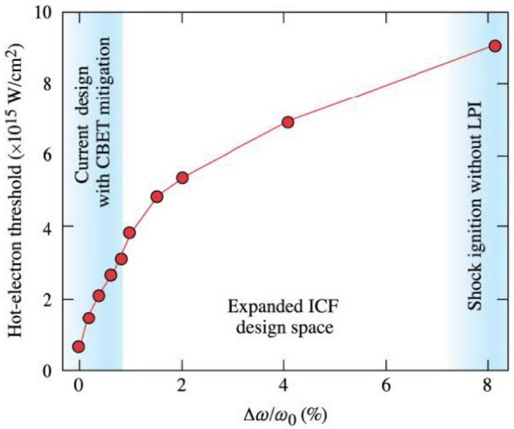
LPI modeling predicts that $\Delta\omega/\omega > 1\%$ mitigates LPI losses, leading to enhanced ablation pressure

- **OMEGA-scale target designs**

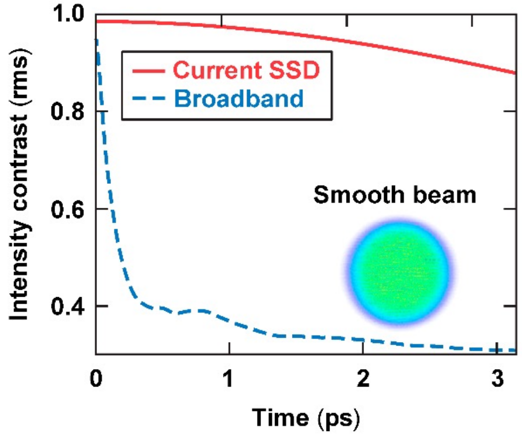
Crossed-beam energy transfer (Increased drive pressure)



Two-plasmon decay (Hot-electron mitigation)



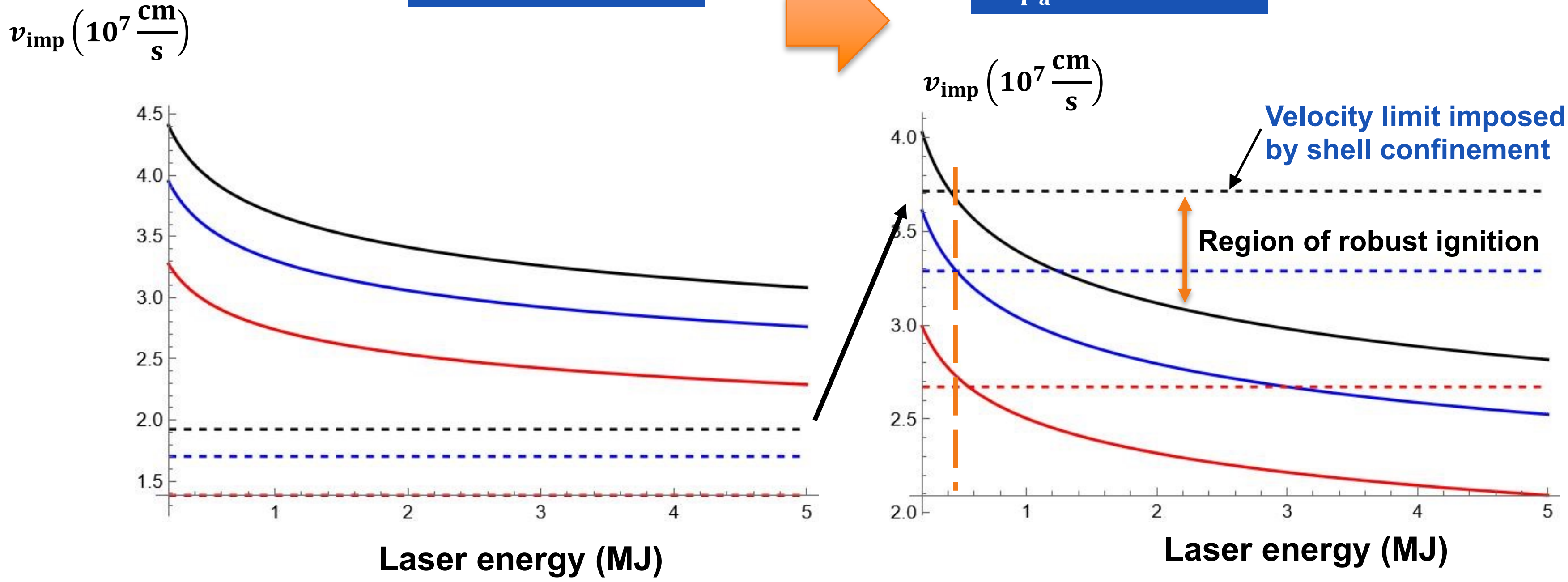
Improved imprint (<1-ps asymptotic smoothing)



Mitigating CBET significantly opens up the ignition parameter space

$p_a = 80$ Mbar

$p_a = 220$ Mbar



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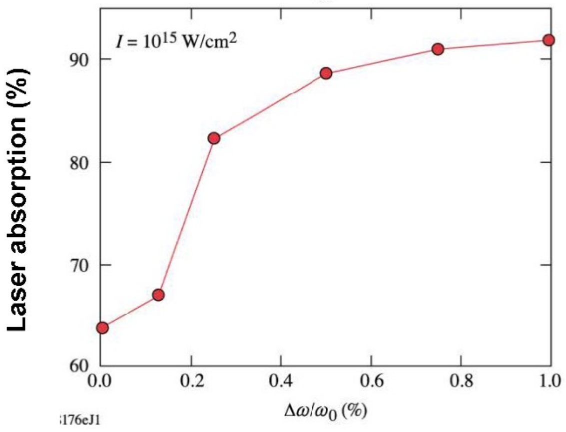

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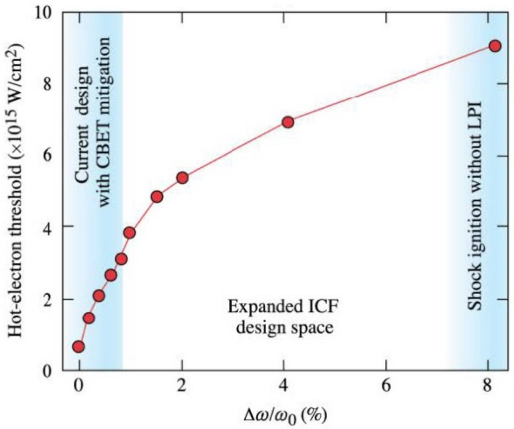

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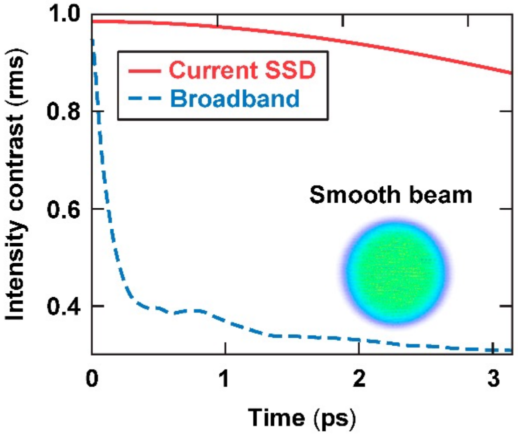
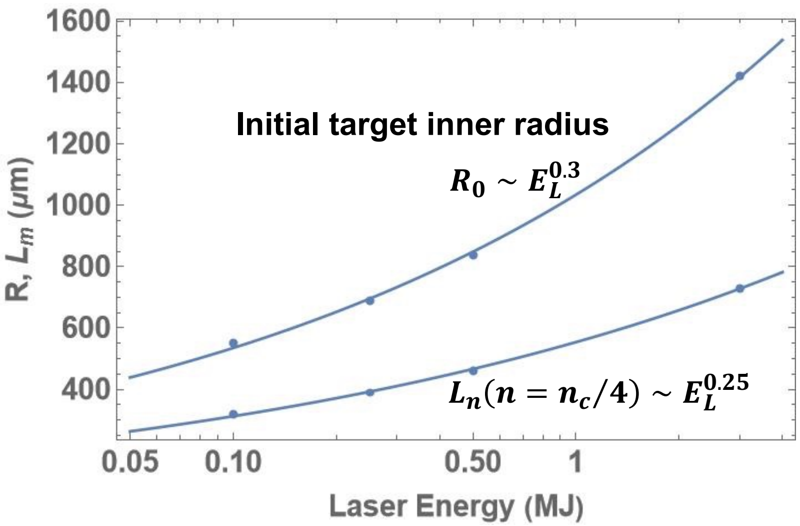
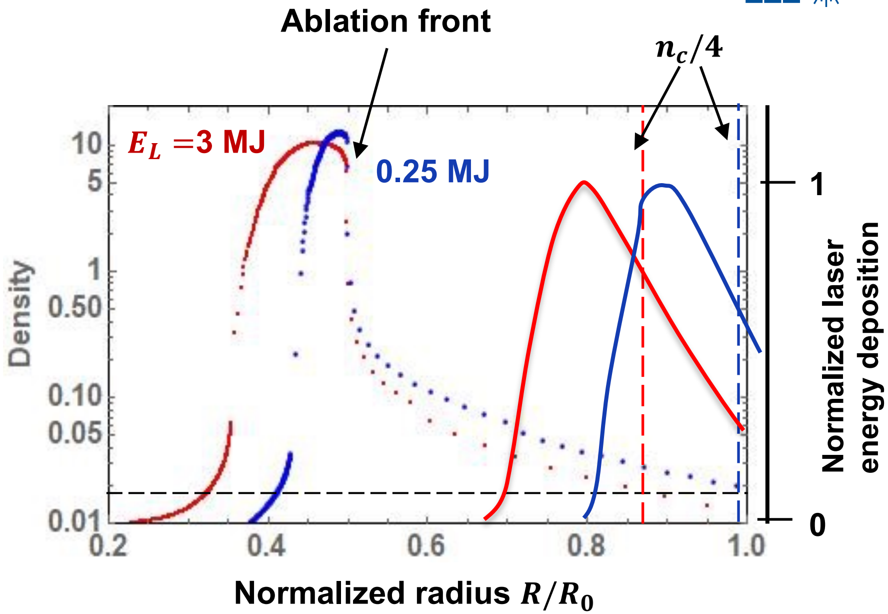


What is the bandwidth requirement at larger laser energies? Let's look at LPI parameters as we scale up the target size and laser energy.

Density scale-length at $n_c/4$ increases slower with laser energy than the initial target radius

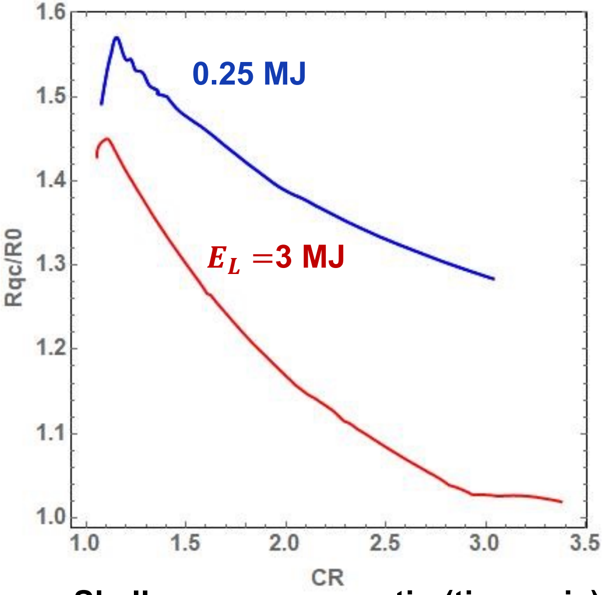
Density scale length at $n_c/4$ is not hydro-equivalent



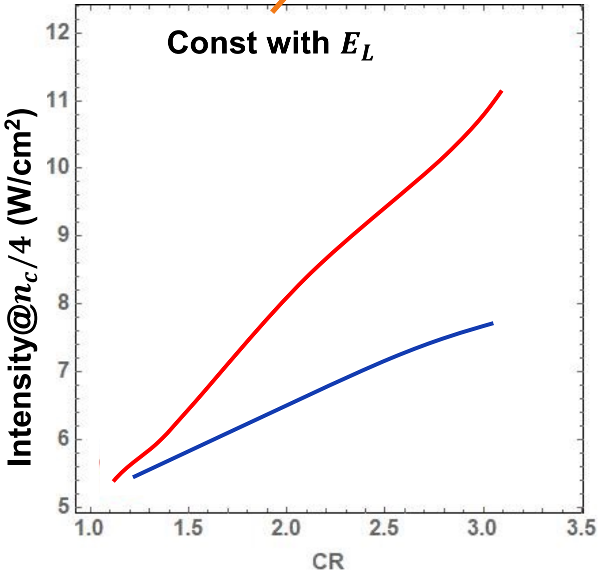


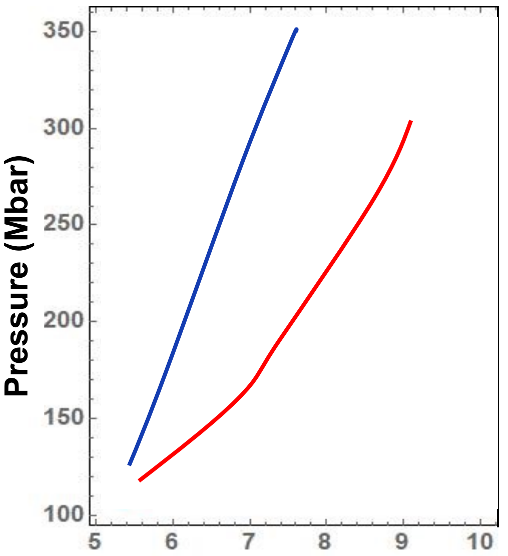
With increased target size at larger drive laser energies, intensity at quarter-critical surface gets larger for a given drive pressure

$$I \sim \frac{Power}{R^2} \sim \left(\frac{Power}{R_0^2}\right) / \left(\frac{R}{R_0}\right)^2$$



Shell convergence ratio (time axis)





Intensity@$n_c/4$ (W/cm^2)

Increased intensity at $n_c/4$ requires larger bandwidth at larger laser energies

Target gain is a simple relation between ablation pressure, implosion velocity, and peak drive intensity

Rocket equation:

$$M_{\mathrm{DT}} \simeq \frac{1}{5}\frac{E_{\mathrm{laser}}}{I_{\max}}\frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}}$$

Burn fraction depends on ρR

Gain = Yield / E_{Laser}

$$G = f_{\mathrm{burn}} M_{\mathrm{DT}}\, \epsilon_{\mathrm{DT}} / E_{\mathrm{L}}$$

Min (v_{imp}) from ignition criterion

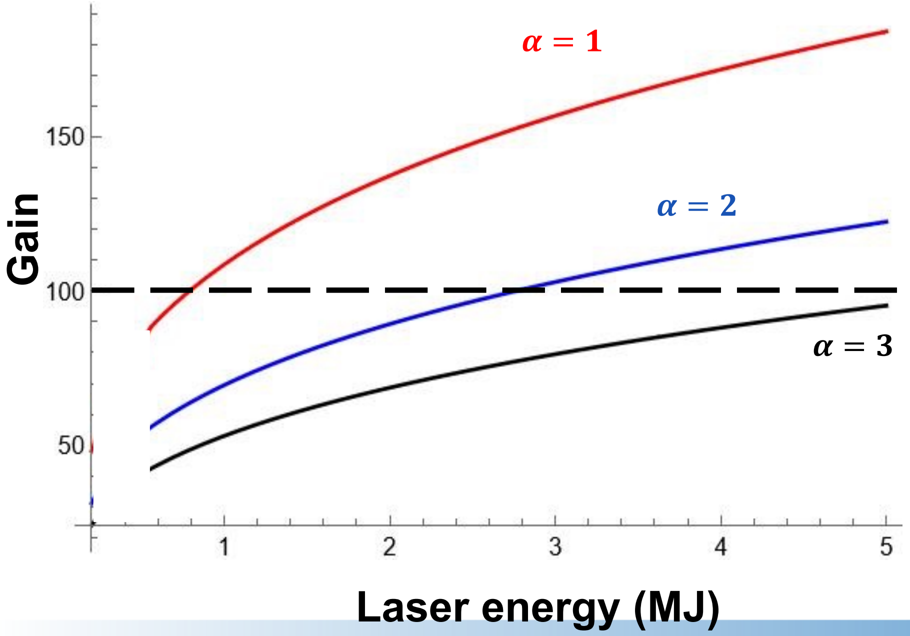
$$\boldsymbol{G \simeq 180\frac{f_{\mathrm{burn}}}{I_{15}}\left(\frac{p_{\mathrm{a}}}{100\ \mathrm{Mbar}}\right)\left(\frac{v_{\mathrm{imp}}}{3\times 10^{7}\,\mathrm{c\,m/s}}\right)^{-1}}$$

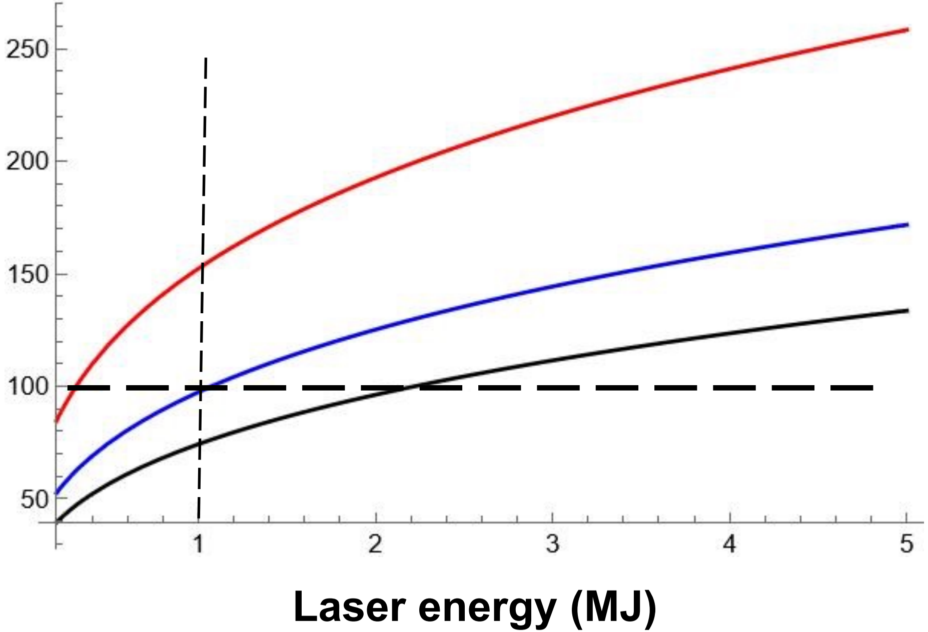
Additional ablation pressure enhancement can be achieved by beam zooming

$p_a = 220$ Mbar

$p_a = 300$ Mbar

Reducing beam size during implosion – beam zooming





How to improve LID and LDD ICF implosion performance and approach high yields

- LID
- Low hot-spot energy (PdV is only ~ 10 kJ on ignition shot) – need small hot spots and high hot spot pressures ($P_{hs} \sim 1/\sqrt{E_{hs}}$) to ignite – large sound speed and PdV losses during expansion (limited shell confinement and fuel burn fraction)
- Higher ablation pressures (~ 150 -170 Mbar) – helps confinement but more will help (hotter hohlraums)

- LDD
- High hot-spot energy (40 – 60 kJ even with CBET) – larger hot spots, lower required hot-spot pressures, lower PdV losses during hot-spot expansion
- Low ablation pressures – low shell confinement (return shock breaks out too early) – need to mitigate CBET and increase p_{abl}

LID
- Increase hot spot energy – larger laser energies, more efficient hohlraums
- Increase ablation pressure – hotter hohlraums

LDD
- Increase ablation pressure – mitigate CBET

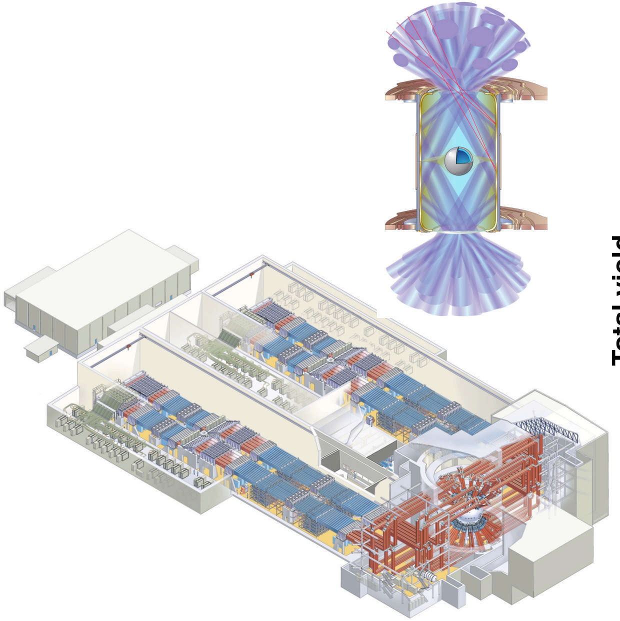
Robust high-yield designs require drive pressure to be increased by a factor of 2 to 3 from current laser direct drive experiments

- In current ICF implosions shell kinetic E_{k} and hot-spot E_{hs} energy are maximized to achieve the best performance
  - E_{k} is maximized by increasing implosion velocity ($v_{\mathrm{imp}} > 4 \times 10^{7}$ cm/s)
  - This requires raising fuel adiabat to maintain stability
  - Current drive pressures in LDD and LID cannot support hot-spot conditions (pressure, convergence) required for robust burn propagation
- In high-gain designs fuel mass must be maximized with ablation pressures in excess of 220 Mbar (at incident intensity of 10^{15} W/cm^2)
  - Implosion velocity v_{imp} needs to be close to the minimum required for ignition
  - Fuel must be kept close to the Fermi degeneracy to maximize convergence and ρR
  - High p_{a} and low v_{imp} lower IFAR, reducing shell susceptibility to short-scale instability growth

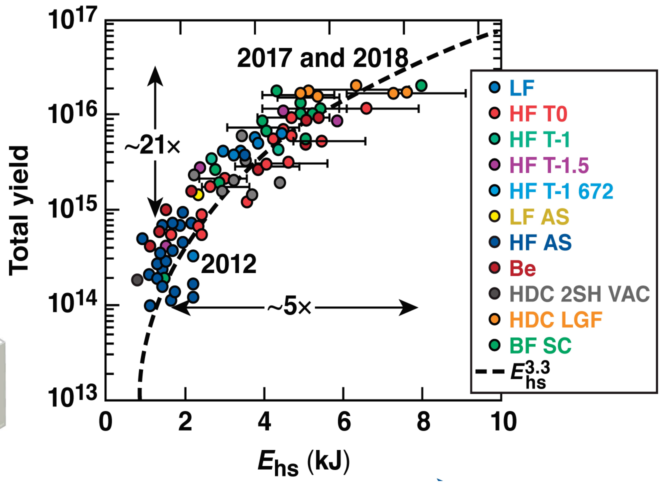
Backup slides

Current ICF results: Record high hot-spot energy led to ignition in laser-indirect-drive implosion on the NIF

Laser-indirect-drive on the NIF

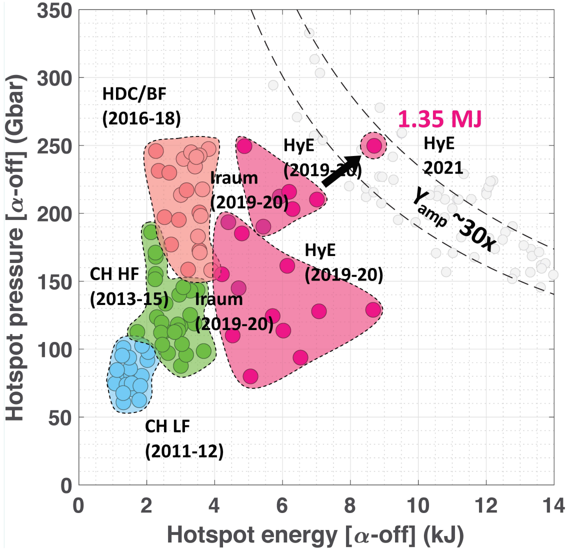


Earlier NIF campaigns



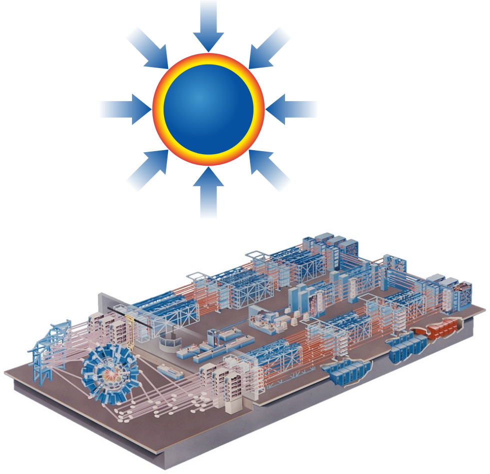
Ignition shot N210808

E_{hs} (no α) ~ 9 kJ

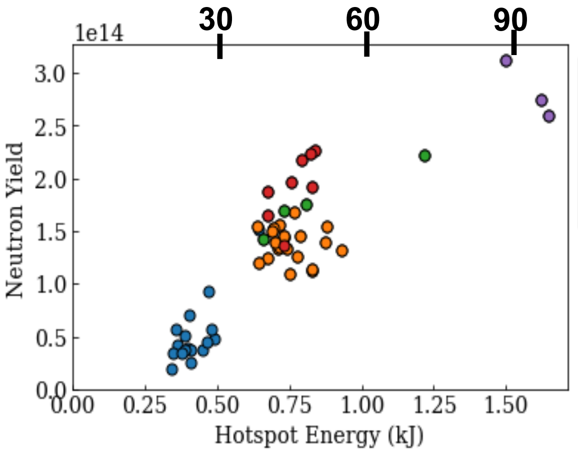


Current ICF results: Target performance improves with increased hot-spot energy in laser-direct-drive implosions on OMEGA

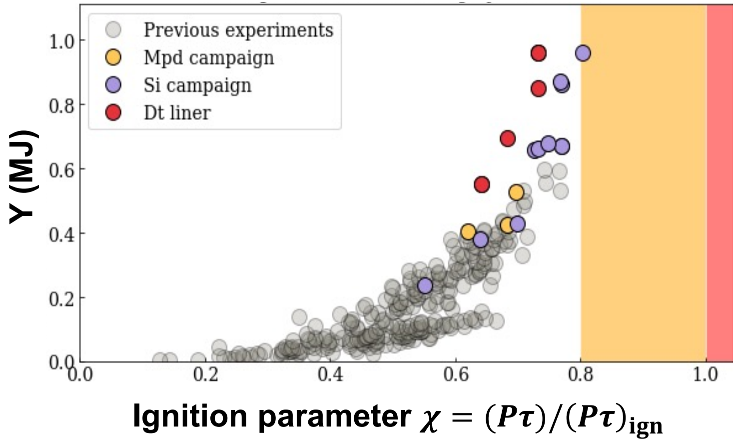
Laser-direct-drive on OMEGA



Neutron yield in LDD cryogenic implosions



Extrapolation of OMEGA results to E_L = 1.9 MJ



LDD implosions couple 3 to 6× larger E_{hs} compared to LID ignition capsules.

Compared to the current ICF implosions, high-gain designs require larger fuel mass, higher compression, and lower implosion velocities

Current implosions

- Maximize shell kinetic E_{k} and hot-spot E_{hs} energy
- Maximize implosion velocity ($v_{\mathrm{imp}} > 4 \times 10^7$ cm/s)
- Fuel adiabat (entropy) must be above a threshold value determined by implosion stability
  - penalty on convergence and fuel areal density (ρR)

High-gain designs

- Fuel mass is maximized
- Minimized implosion velocity ($v_{\mathrm{imp}} < 3 \times 10^7$cm/s) while still satisfying Lawson's criterion
- Fuel must be kept close to Fermi degeneracy
  - This will maximize convergence and ρR

How to bridge the gap?

The highest leverage – increasing the drive pressure by mitigating LPI losses!

Robust high-yield designs require drive pressure to be increased by a factor of 2 to 3 from current laser direct drive experiments

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- Current ICF implosions maximize shell kinetic E_{k} and hot-spot E_{hs} energy to achieve best performance
  - E_{k} is maximized by increasing implosion velocity ($v_{\mathrm{imp}} > 4 \times 10^7$ cm/s)
  - Fuel adiabat is increased above to maintain stability
  - Current drive pressures in LDD and LID cannot support hot-spot conditions (pressure, convergence) required for robust burn propagation
- Fuel mass must be maximized in high-gain designs with ablation pressures in excess of 220 Mbar
  - Implosion velocity v_{imp} need to be close to the minimum required for ignition
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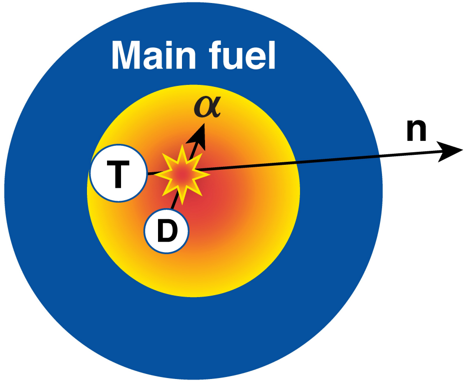
  - High p_{a} and low v_{imp} lower IFAR, reducing shell susceptibility to short-scale instability growth

The high-level requirements for ~100-MJ yields



- Neutron yield: $Y_n = M_{burn}\epsilon_{DT}$, $\epsilon_{DT} = 2.75 \times 10^{11}$ J/g

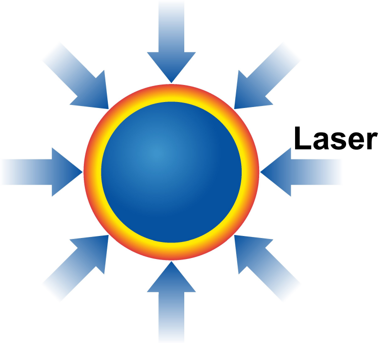
  $M_{burn} = 3.7\ \mu g$ for $Y_n = 1$ MJ

- To get $Y_n = 100$ MJ: $M_{burn} = 0.37$ mg
- Assume burn fraction $f_{burn} \sim 1/4$: $M_{DT} = 1.5$ mg (depends on ρR)
- We want to accelerate this mass to $v_{imp} \sim 3 \times 10^7$ cm/s

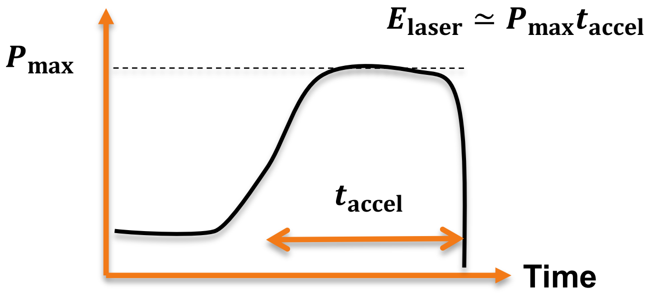
- This requires $E_k = \frac{1}{2} M_{DT} v_{imp}^2 = 70$ kJ
- Current LID NIF: $E_k \sim 20$ kJ
- Scaled LDD OMEGA implosions to NIF energies : $E_k = 60$ to 80 kJ

- Energetically, LDD makes more sense for high yields
- Low drive pressures in current LDD experiments provide poor shell confinement

Shell kinetic energy mainly depends on ablation pressure, at a given intensity, and implosion velocity



Laser power



$$M_{\mathrm{DT}} \frac{v_{\mathrm{imp}}}{t_{\mathrm{accel}}} \simeq 4\pi R_{\mathrm{target}}^2 p_{\mathrm{a}}$$

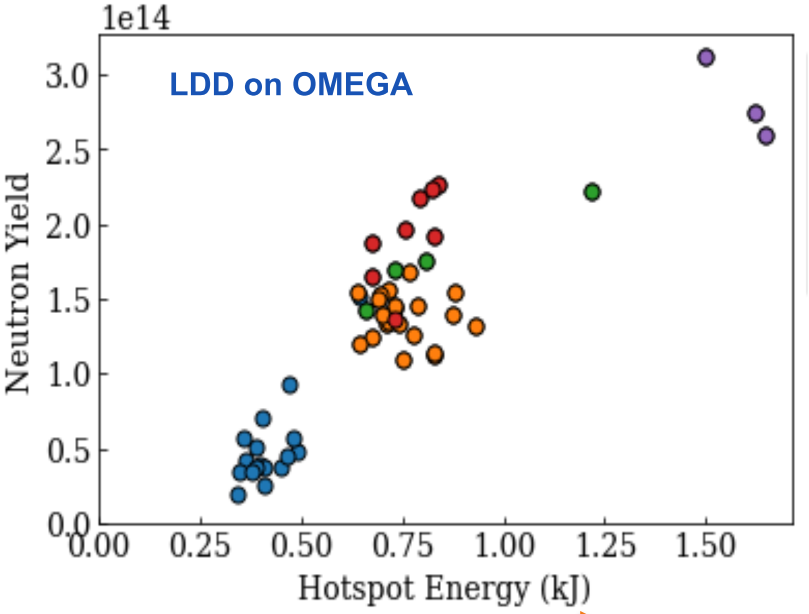
$$M_{\mathrm{DT}} \sim E_{\mathrm{laser}} \frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}} \underbrace{\left(\frac{4\pi R^2}{P_{\max}}\right)}_{\text{Peak laser intensity } I_{\max}^{-1}}$$

$$M_{\mathrm{DT}} \sim \frac{E_{\mathrm{laser}}}{I_{\max}} \frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}}$$

$$\boxed{\frac{M v_{\mathrm{imp}}^2}{E_{\mathrm{L}}} = \eta_{\mathrm{hydro}} \sim \frac{p_{\mathrm{a}} v_{\mathrm{imp}}}{I_{\max}}}$$

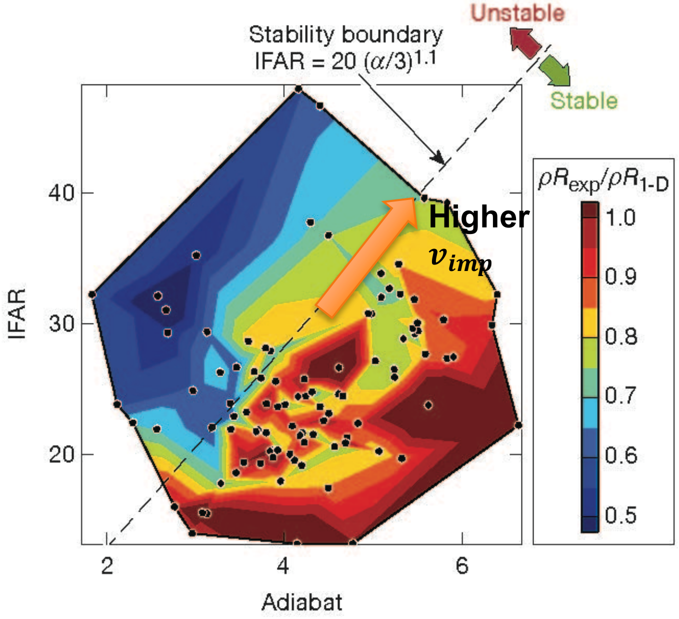
Kinetic energy in current high-performing LDD implosions is maximized by increasing v_{imp} to 500 to 600 km/s

$$\frac{M v_{\mathrm{imp}}^2}{E_{\mathrm{L}}} = \eta_{\mathrm{hydro}} \sim \frac{p_{\mathrm{a}} v_{\mathrm{imp}}}{I_{\mathrm{max}}}$$



Thinner shells, higher v_{imp}

Stability in current implosions on OMEGA is achieved by increased adiabat

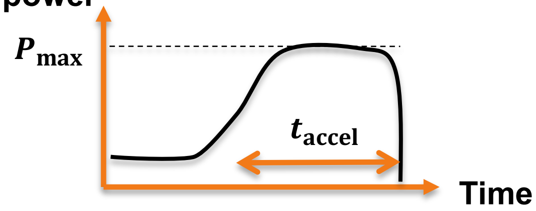


Accelerating the amount of fuel necessary for high gains, however, requires higher ablation pressures

$$M_{\mathrm{DT}} \simeq \frac{1}{5} \frac{E_{\mathrm{laser}}}{I_{\max}} \frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}}$$

$$\frac{p_{\mathrm{a}}}{I_{\max}} \simeq 5 \frac{M_{\mathrm{DT}} v_{\mathrm{imp}}}{E_{\mathrm{laser}}}$$

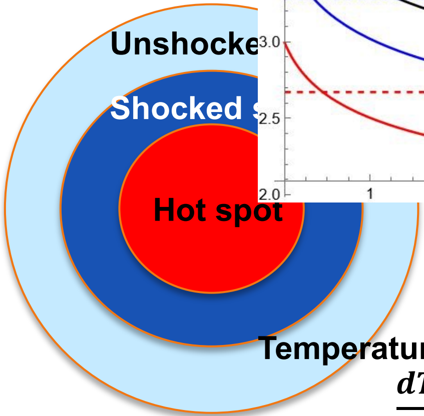
To maximize the yield, velocity needs to be minimized

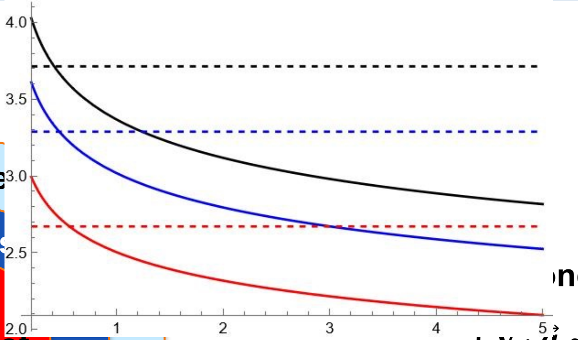


To accelerate $M_{\mathrm{DT}} = 1.5$ mg to $v_{\mathrm{imp}} = 3 \times 10^7$ cm/s at $E_{\mathrm{laser}} \sim 1$ MJ requires $p_{\mathrm{a}} > 220$ Mbar at $I \sim 10^{15}$ W/cm^2.

- Implosions on OMEGA reach p_{a} ~ 120 to 140 Mbar, $p_{\mathrm{a}} \sim 80$ Mbar on the NIF
- LID implosions on the NIF peak at $p_{\mathrm{a}} \sim 150$ to 170 MBar

As the required shell velocity decreases with laser energy, the PdV losses get reduced





Time scale: δt

$$\ddot{R} \sim \frac{S_{hs} P_{hs}}{M_{shocked}} \sim \frac{R_{hs}(P_{hs} R_{hs})}{M_{shocked}}$$

nduction loss:

$$\int_V \nabla \cdot \vec{q} \sim R_{hs}^2 q \sim \frac{R_{hs}^2 P_{hs} V_a \rho_{sh}}{\rho_{hs}} \sim R_{hs} c_{hs}^2 \kappa_{hs}$$

Temperature evolution: source and sink balance:

$$\frac{dT}{dt} = \frac{T_{hs}}{E_{hs}} \left(f_\alpha Q_\alpha - Q_{rad} - Q_e - P \frac{dV}{dt} \right)$$

$$\dot{R}_{hs} \sim c_{shell} \sim P_{hs}^{\frac{1}{5}} \alpha_s^{\frac{3}{10}}$$

$$\alpha_s \sim \alpha_i^{\frac{4}{5}} v_{imp}^{\frac{2}{3}}$$

pdV loss term: $P_{hs} R_{hs}^2 \dot{R}_{hs} \sim (P_{hs} R)\, R_{hs} \dot{R}_{hs}$

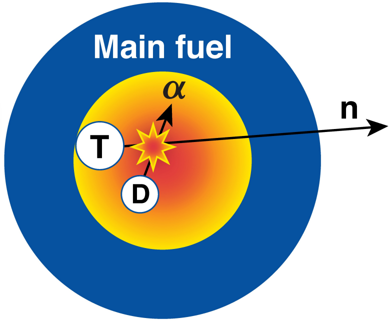
Alpha-production: $Q_\alpha \sim \frac{\sigma v}{T^2} P_{hs}^2 R_{hs}^3 \sim \left(\frac{\sigma v}{T^2}\right) (P_{hs} R_{hs})^2 R_{hs}$

Radiation: $Q_{rad} \sim \frac{P_{hs}^2 R_{hs}^3}{T_{hs}^{1.3}} \sim (P_{hs} R_{hs})^2 R_{hs} \frac{1}{T_{hs}^{1.3}}$

Fuel mass and hot-spot assembly in high-yield implosions

Igniting hot spot

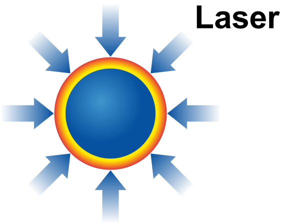
$P_{\mathrm{hs}}R_{\mathrm{hs}} > 1\ \mathrm{Gbar} \times \mathrm{cm}$
$T_{\mathrm{i}} > 4.5\ \mathrm{keV}$



+

Fuel mass for $G \gg 1$

Pressure drive acceleration to v_{imp}



- Shell kinetic energy and uniformity are not sufficient to guarantee ignition and burn
- Shell must also provide robust confinement at peak compression

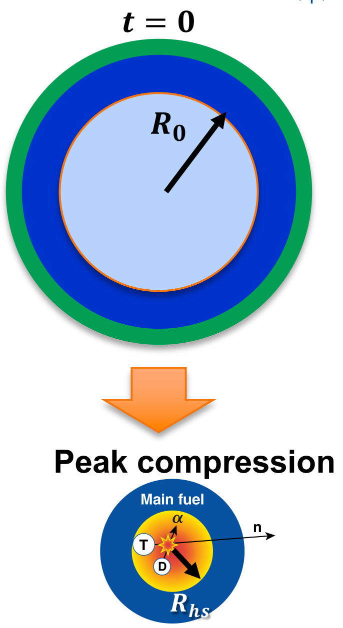
What is the minimum shell velocity required for ignition?

Creating an igniting hot spot: $(\rho R)_{\rm hs} T_{\rm hs} = 0.3\ \mathrm{g/cm^2} \times 5\ \mathrm{keV} \rightarrow$

Ignition parameter: $\boxed{P_{\rm hs} R_{\rm hs} > 1\ \text{Gbar} \times \text{cm},\ T_{\rm i} > 4.5\ \text{keV}}$

Hot spot pressure: $$P_{\rm hs} \sim \frac{p_{\rm a}^{1/3} v_{\rm imp}^{10/3}}{\alpha}$$

Hot-spot radius: $$R_{\rm hs} \sim \alpha^{1/5} \left(\frac{E_{\rm L}}{I v_{\rm imp} p_{\rm a}^{1/5}} \right)^{1/3}$$



What is the minimum shell velocity required for ignition?

$$P_{\mathrm{hs}} \sim \frac{p_{\mathrm{a}}^{1/3} v_{\mathrm{imp}}^{10/3}}{\alpha} \qquad R_{\mathrm{hs}} \sim \alpha^{1/5}\left(\frac{E_{\mathrm{L}}}{I v_{\mathrm{imp}} p_{\mathrm{a}}^{1/5}}\right)^{1/3}$$

Ignition parameter:

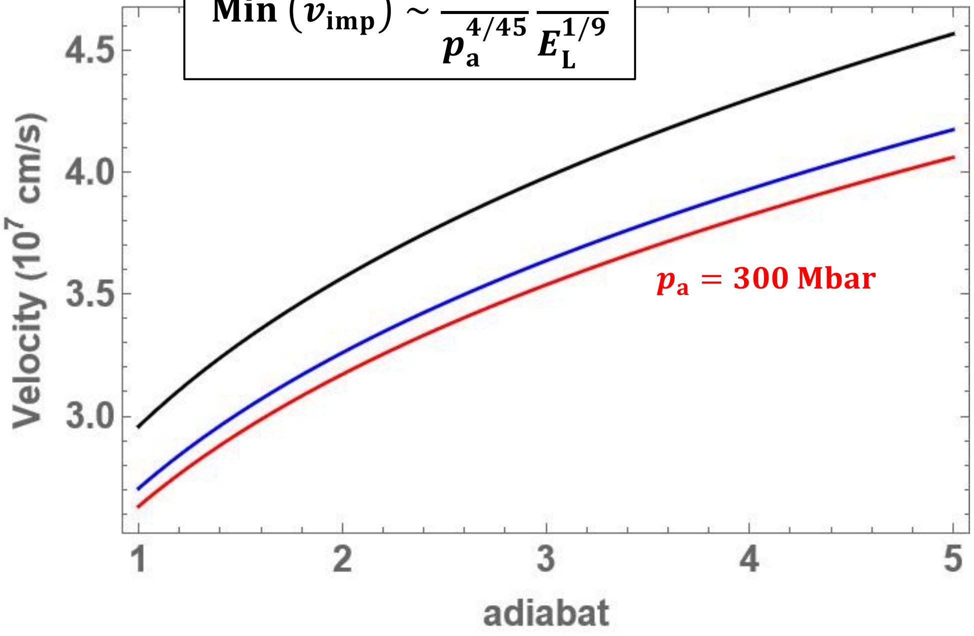
$$P_{\mathrm{hs}} R_{\mathrm{hs}} \sim v_{\mathrm{imp}}^{3}\left(\frac{E_{\mathrm{L}}}{I}\right)^{1/3} \frac{p_{\mathrm{a}}^{4/15}}{\alpha^{4/5}} > (PR)_{\mathrm{min}}$$

Minimum velocity for ignition:

$$\mathrm{Min}\left(v_{\mathrm{imp}}\right) \sim \frac{\alpha^{4/15}}{p_{\mathrm{a}}^{4/45}} \frac{I^{1/9}}{E_{\mathrm{L}}^{1/9}} = \left(\frac{\alpha^{12/5}}{p_{\mathrm{a}}^{4/5}} \frac{I}{E_{\mathrm{L}}}\right)^{1/9}$$

Examples for 500-kJ laser energy

$$\text{Min}\left(v_{\text{imp}}\right) \sim \frac{\alpha^{4/15}}{p_{\text{a}}^{4/45}} \frac{I^{1/9}}{E_{\text{L}}^{1/9}}$$



80 Mbar CBET losses

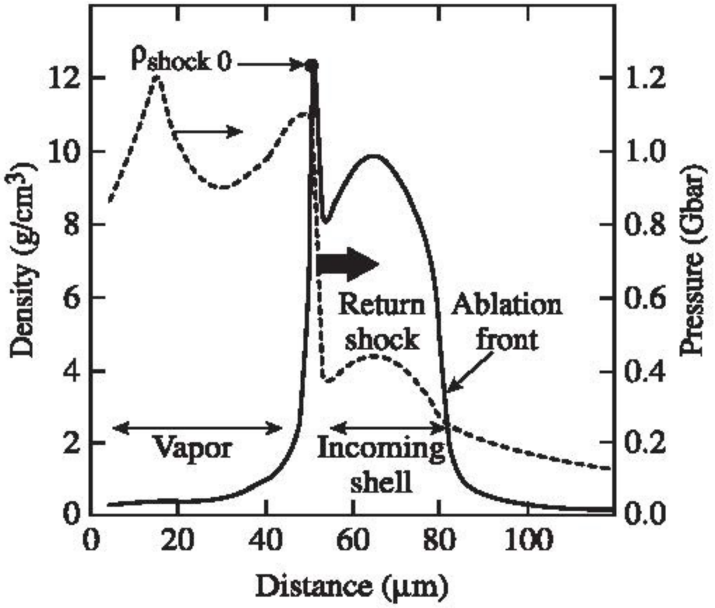
220 Mbar No LPI

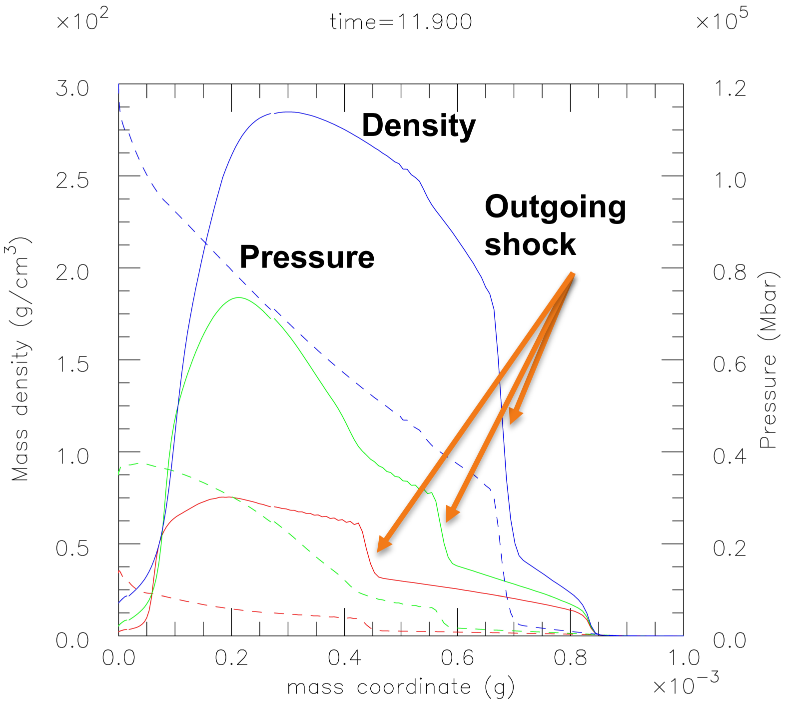
No LPI, zooming

The limit on maximum velocity is set by shell confinement.

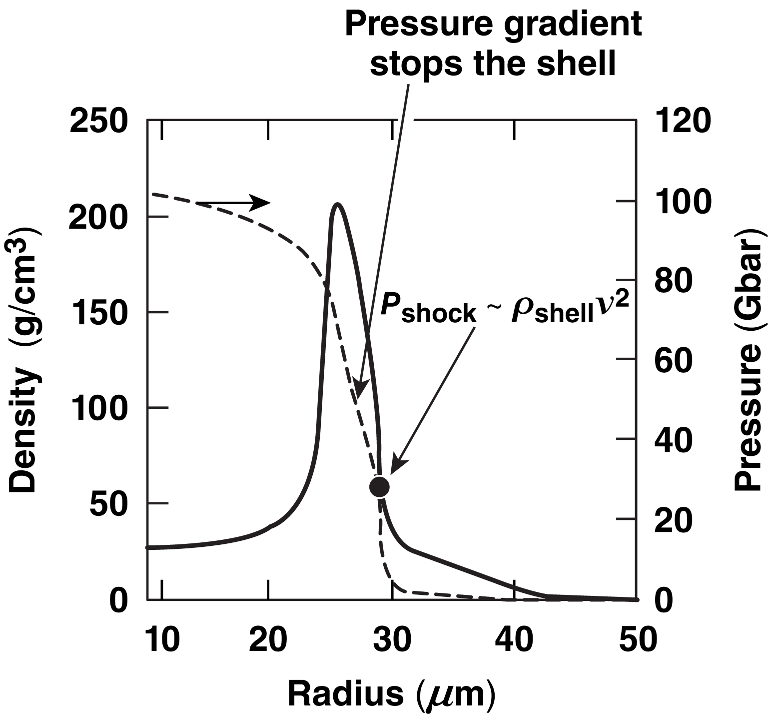
Shell confinement is limited to outgoing shock propagation time

Shock is launched into the shell at the beginning of deceleration





Two scenarios for shell deceleration



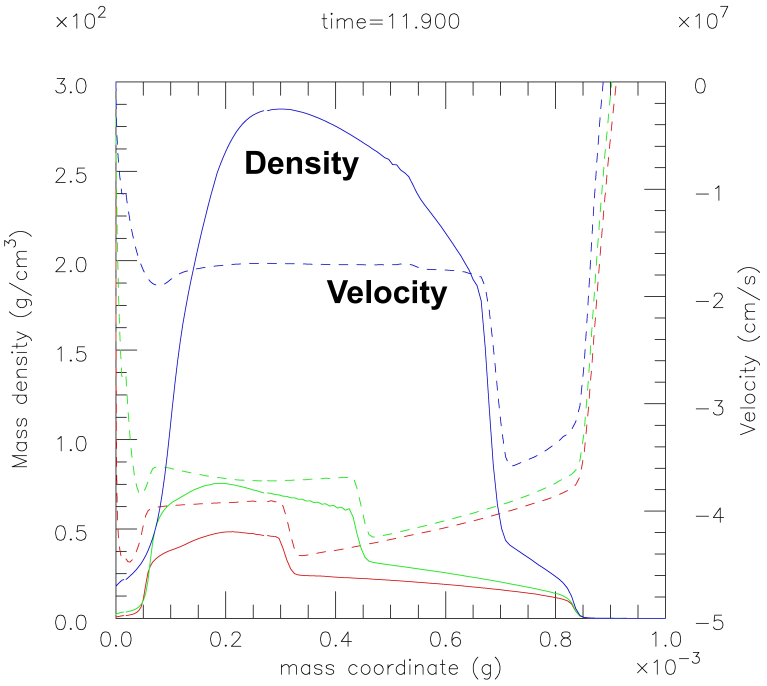
Case 1: Shock breaks out of the shell while $\dot{R}_{hs} < 0$

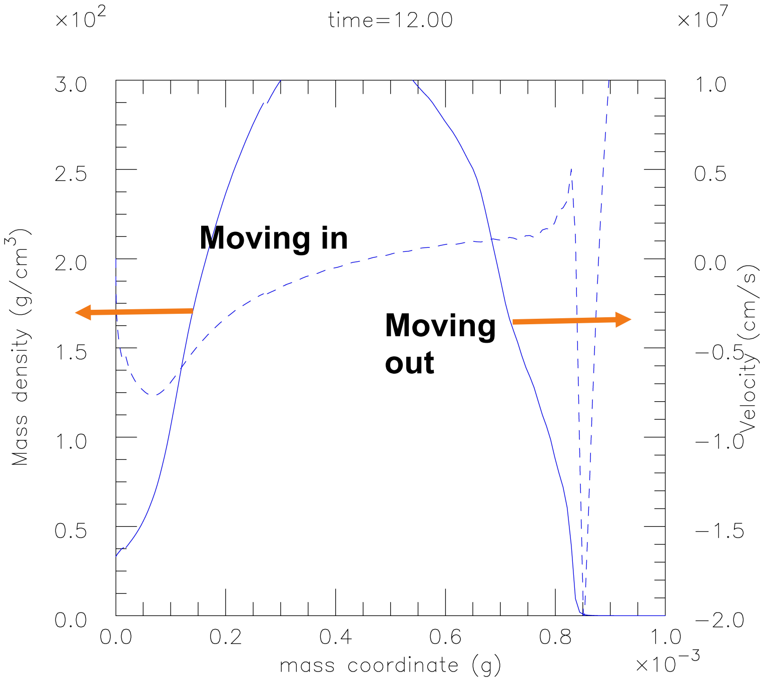
- Inefficient $E_k \rightarrow E_{hs}$
- Marginal ignition or low-gain designs

Case 2: Hot spot stops converging before shock breaks out of the shell

High-gain designs

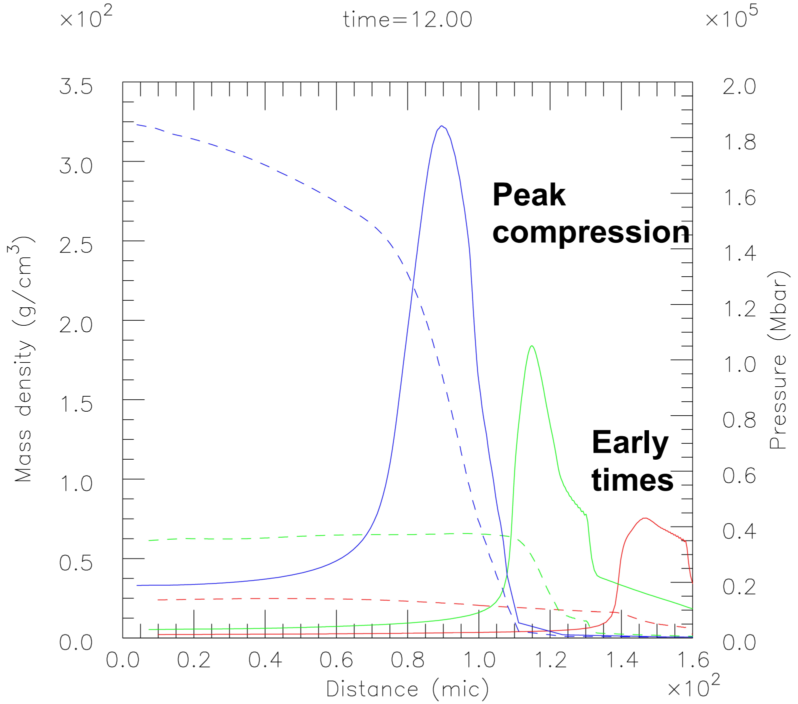
Case1: Shock breaks out of the shell before hot-spot stagnation ($\dot{R}_{\mathbf{hs}} < 0$)





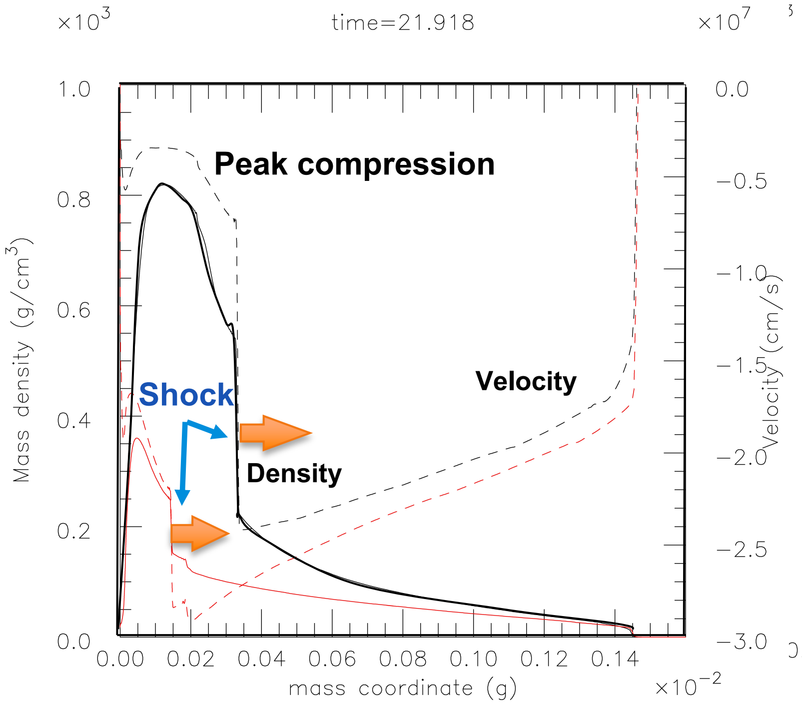
- "Poor" shell convergence
- Shell does not stagnate, even in 1-D

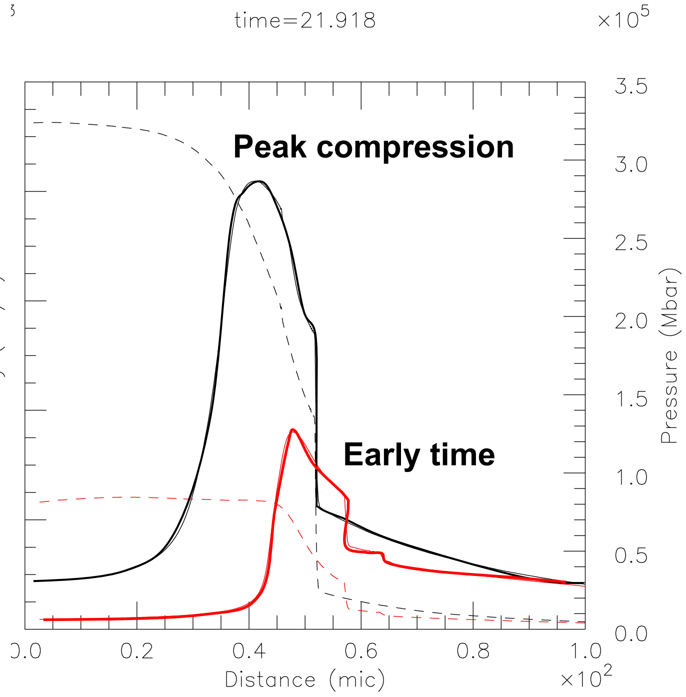
Shell stagnates at larger radius, in this case with poor shell-to-hot-spot energy conversion



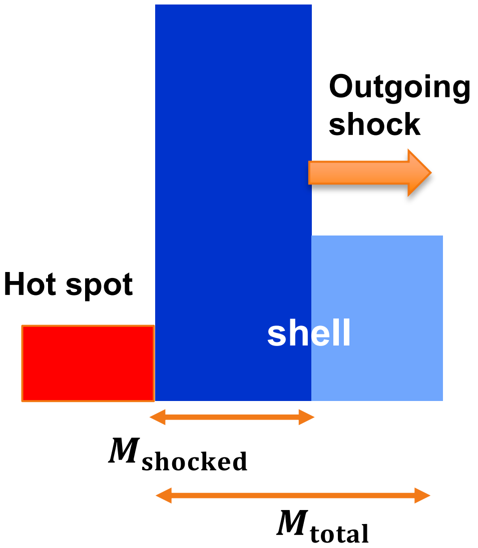
- Even with significant shell kinetic energy, hot-spot energy density is low
- As alpha heating increases, *PdV* losses dominate over alpha deposition – gain ~ 1 is possible but not efficient burn of the main fuel

Case 2: Hot spot stagnates while shock is inside the shell (preferred configuration)





Optimizing hot-spot confinement requires reaching inner shell stagnation before the outgoing shock breaks out of the shell



Efficient compression

At stagnation: $M_{\text{shocked}} < M_{\text{total}}$

$$v_{\text{imp}} < 2.6 \times 10^7 \text{cm/s}\ \alpha^{0.3} \left(\frac{p_{\text{a}}}{100\ \text{Mbar}}\right)^{0.65}$$

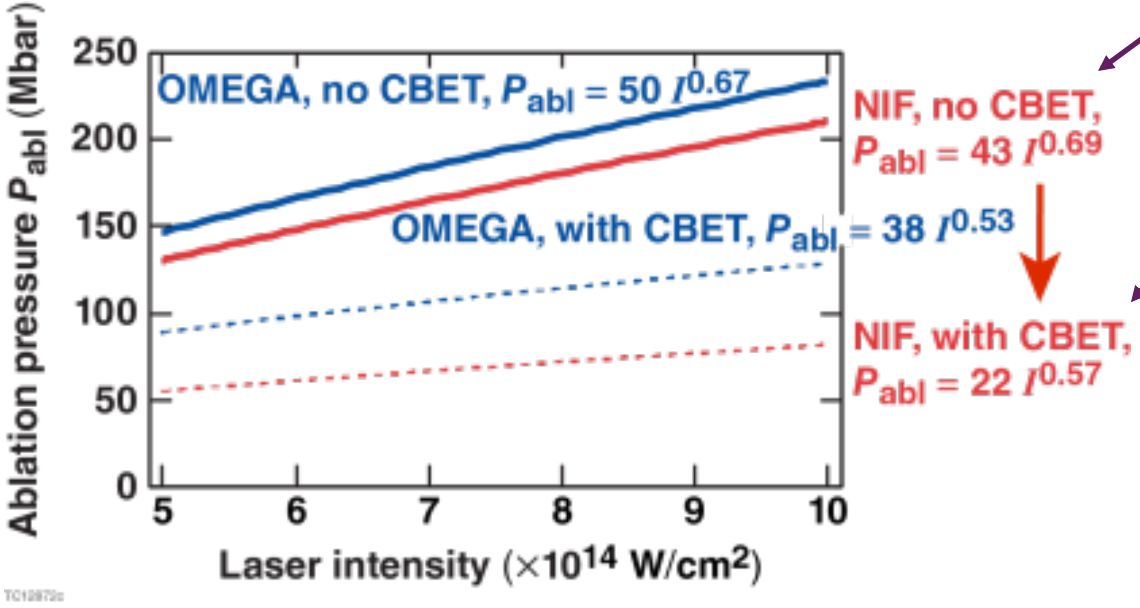
Because of instabilities at ablation front: $M_{\text{shocked}} < 0.5\ M_{\text{total}}$

$$v_{\text{imp}} < 1.6 \times 10^7 \text{cm/s}\ \alpha^{0.3} \left(\frac{p_{\text{a}}}{100\ \text{Mbar}}\right)^{0.65}$$

Ablation pressure sets the limit on the maximum implosion velocity for an efficient piston.

Ablation pressure depends on the details of the laser–plasma interaction

Direct drive, $\lambda_L = 351$ nm



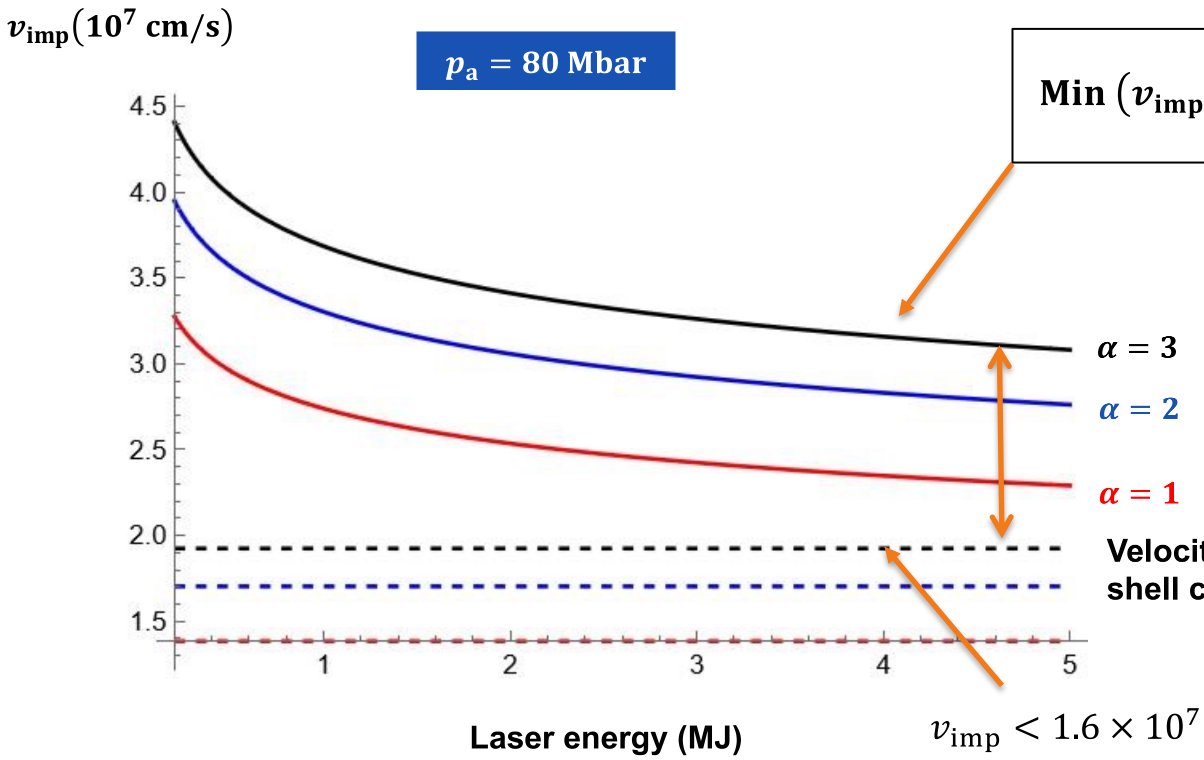
Bremsstrahlung absorption:

Bremsstrahlung + CBET losses:

Coupling losses due to CBET prevent achieving igniting hot spots

$p_a = 80\ \text{Mbar}$

$$\text{Min}\left(v_{\text{imp}}\right) \sim \frac{\alpha^{4/15}}{p_a^{4/45}} \frac{I^{1/9}}{E_L^{1/9}}$$



Velocity limit imposed by shell confinement

$$v_{\text{imp}} < 1.6 \times 10^7\,\text{cm/s}\ \alpha^{0.3} \left(\frac{p_a}{100\ \text{Mbar}}\right)^{0.65}$$

Hot-spot formation and shell confinement requirements do not overlap—no robust ignition is possible.

Mitigating CBET significantly opens up the ignition parameter space

Laser and kinetic energy required for "robust" burn

$$\text{Min}\left(v_{\text{imp}}\right) \sim \frac{\alpha^{4/15}}{p_{\text{a}}^{4/45}} \frac{I^{1/9}}{E_{\text{L}}^{1/9}}$$

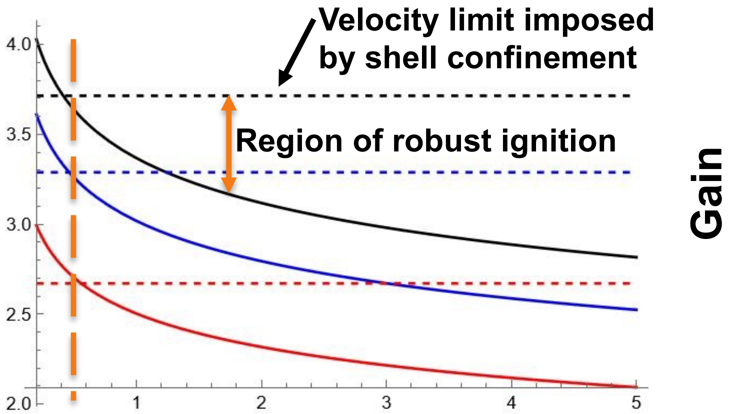
=

$$v_{\text{imp}} < 1.6 \times 10^7 \text{cm/s}\ \alpha^{0.3} \left(\frac{p_{\text{a}}}{100\ \text{Mbar}}\right)^{0.65}$$

$$E_{\text{k}}(\text{kJ}) > 156 \left(\frac{p_{\text{a}}}{100\ \text{Mbar}}\right)^{-5}$$

$p_{\text{a}} = 220\ \text{Mbar}$

$v_{\text{imp}}(10^7 \text{cm}/s)$



Laser energy (MJ)

Current LID: $P_{\text{a}} \simeq 150\ \text{Mbar} \rightarrow E_{\text{k}} > 20\ \text{kJ}$ **– right at the edge**

Required energy increases rapidly with reduced drive pressure $P_{\text{a}} = 100\ \text{Mbar} \rightarrow E_{\text{k}} > 156\ \text{kJ}$

Target gain is a simple relation between ablation pressure, implosion velocity, and peak drive intensity

$$M_{\mathrm{DT}} \simeq \frac{1}{5}\frac{E_{\mathrm{laser}}}{I_{\max}}\frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}}$$

$$G = f_{\mathrm{burn}} M_{\mathrm{DT}}\, \epsilon_{\mathrm{DT}}/E_{\mathrm{L}}$$

$$\boldsymbol{G \simeq 180\frac{f_{\mathrm{burn}}}{I_{15}}\left(\frac{p_{\mathrm{a}}}{100\ \mathrm{Mbar}}\right)\left(\frac{v_{\mathrm{imp}}}{3\times 10^{7}\,\mathrm{cm/s}}\right)^{-1}}$$

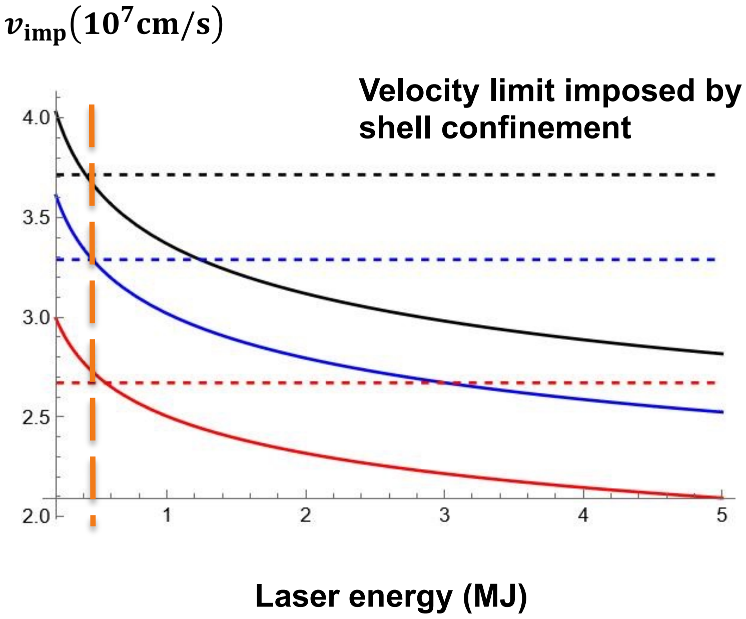
For LDD implosions $p_{\mathrm{a}} = p_{\mathrm{a}}(I)$ depends on thermal conduction and LPI

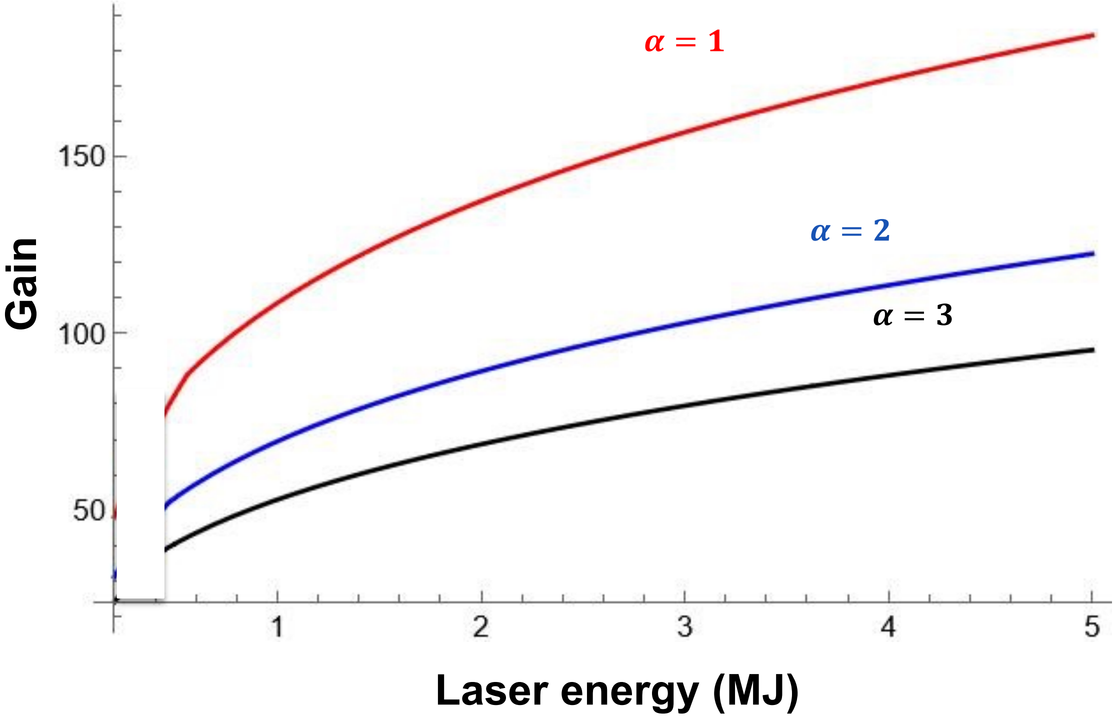
- **This gain relation does not explicitly depend on laser energy E_{L}**
- **Minimum v_{imp} and $f_{\mathrm{burn}}(\rho R)$ depend on E_{L}**

$$\boxed{v_{\mathrm{imp}}(E_L), f_{\mathrm{burn}}\,(E_{\mathrm{L}}) \rightarrow G\,(E_{\mathrm{L}})}$$

Mitigating CBET significantly opens up the ignition parameter space

$p_a = 220$ Mbar

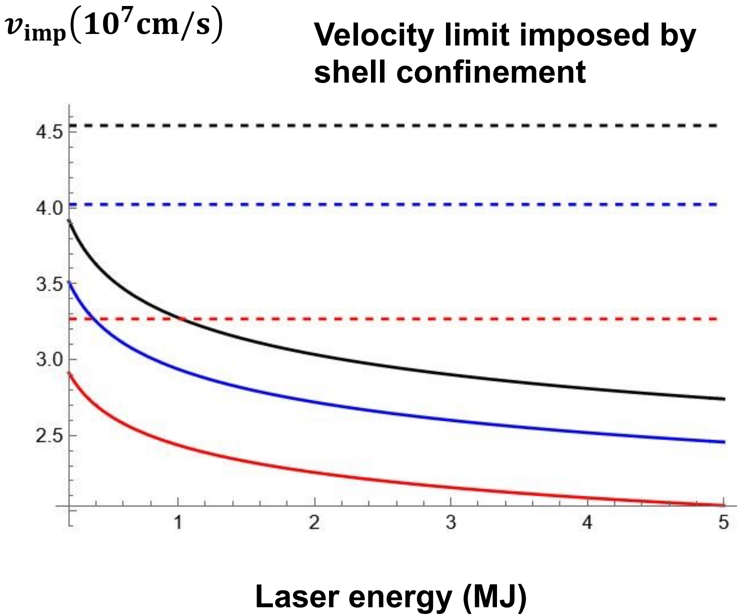


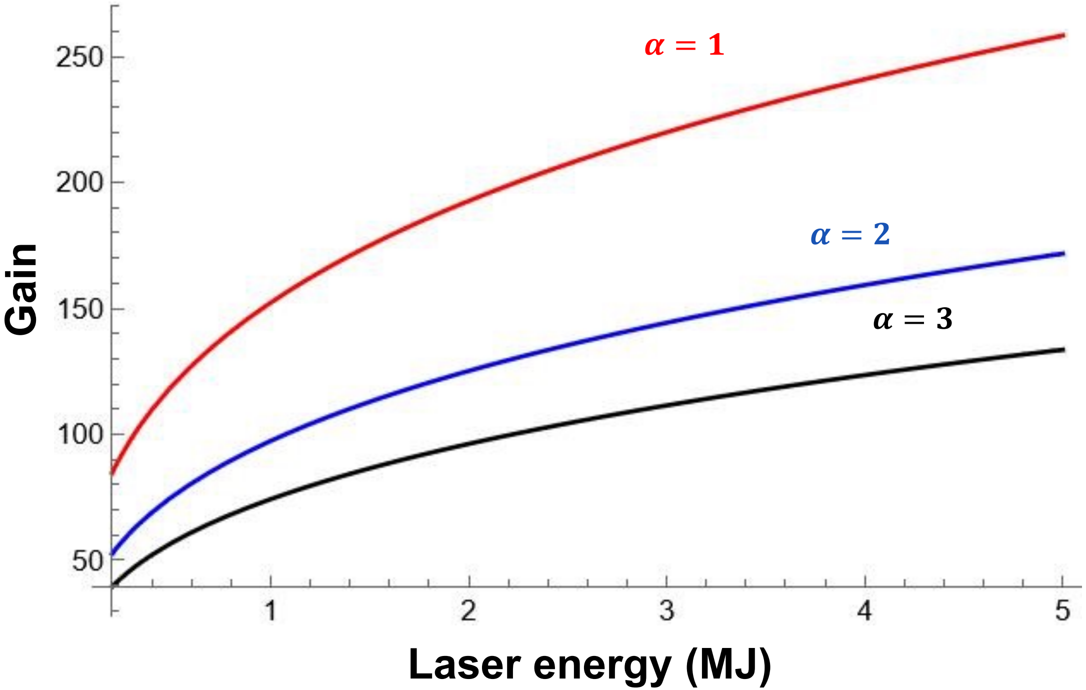


Beam zooming allows accessing lower laser drive energies for ignition

$p_a = 300$ Mbar

One-stage zooming





LPI modeling predicts that $\Delta\omega/\omega > 1\%$ bandwidth increases laser coupling, leading to more massive and hydrodynamically robust LDD implosions

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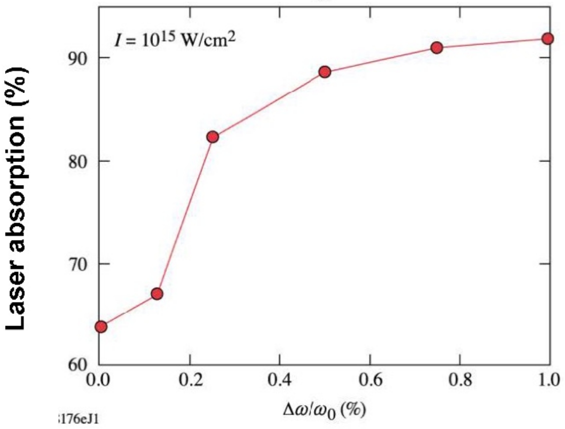
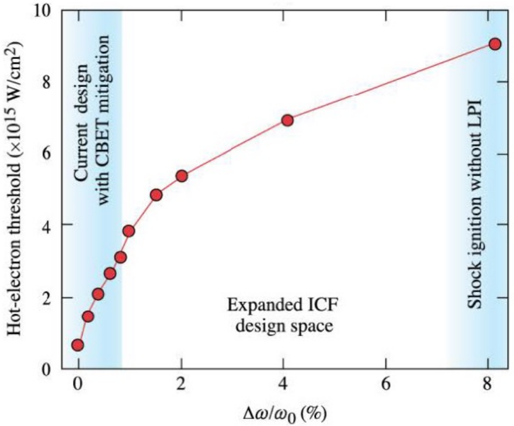
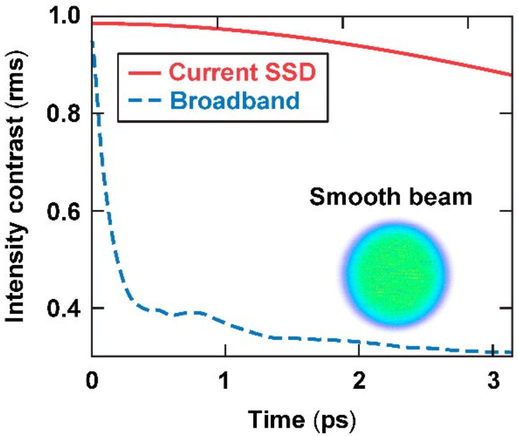
Crossed-beam energy transfer (Increased drive pressure)



Two-plasmon decay (Hot-electron mitigation)



Improved imprint (<1-ps asymptotic smoothing)



Increasing $\Delta\omega/\omega$ > 0.5% will allow stable implosions on OMEGA (IFAR = 15)

Increasing $\Delta\omega/\omega$ > 1% will mitigate both CBET and hot electrons

Improved imprint will expand the direct-drive design space by increasing the hydrostability threshold

LLE is exploring higher-bandwidth driver concepts ($\Delta\omega/\omega > 3\%$) to expand the ignition parameter space for future MJ-class facilities

*R. Follett *et al.*, Phys. Plasmas 26, 062111 (2019).

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Drive pressures in ICF implosions need to be improved by a factor of 2 to 3 from current experiments to make the high-gain targets a reality

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- Current ICF implosions maximize shell kinetic E_k and hot-spot E_hs energy to achieve best performance
  - E_k is maximized by increasing coupling and implosion velocity ($v_\mathrm{imp} > 4 \times 10^7$cm/s)
  - Fuel adiabat is increased above the threshold value to maintain stability
  - Current drive pressures in LDD and LID cannot support hot-spot conditions (pressure, convergence) required for robust burn propagation
- Fuel mass must be maximized in high-gain designs with ablation pressures in excess of 220 Mbar
  - Implosion velocity v_imp need to be close to the minimum required for ignition
  - Fuel must be kept close to Fermi degeneracy to maximize convergence and ρR
  - High p_a and low v_imp lower IFAR, reducing shell susceptibility to short-scale instability growth