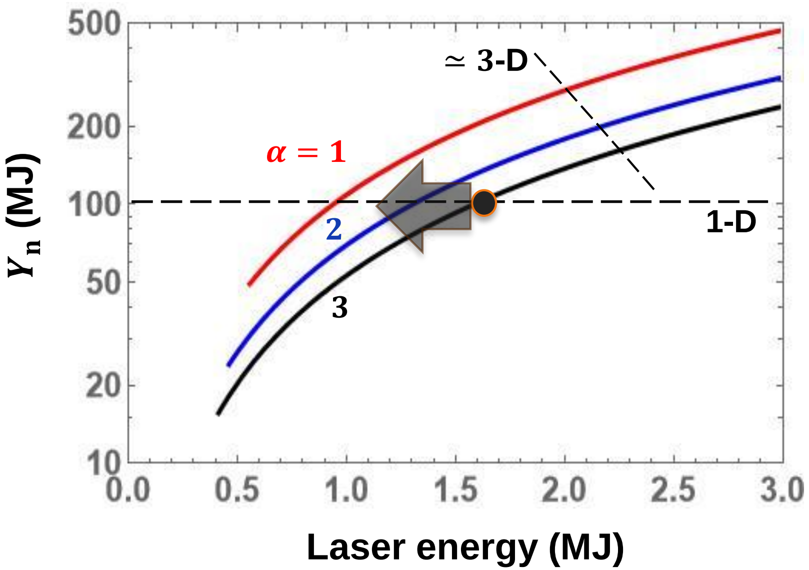
Physics Requirements for High-Gain Inertial Fusion Target Designs



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Summary

Mitigating laser–plasma interaction losses and increasing drive pressure are key elements in achieving 100s-MJ yields in ICF implosions

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- New broadband laser technologies are predicted to mitigate the deleterious effects of laser–plasma interaction (LPI), significantly ($\sim 3\times$) increasing ablation pressures and opening up design parameter space for achieving high yields (>100 MJ) with laser-direct drive LDD at moderate laser energies* ($E_L \sim 1$ MJ)
- Including additional ablation-pressure enhancement strategies such as beam zooming and early-time laser intensity increase allows high-gain designs to increase the fuel adiabat to $\alpha \sim 3$ at $E_\mathrm{L} \sim 1$ MJ
- LPI mitigation strategies, achievable ablation pressures, and physics of high-yield designs must be demonstrated on a sub-scale broadband implosion facility**

* W. Trickey, Uo04:13
** J. Marozas, CO04:15, next talk
P.W. McKenty, JO04:14

Collaborators

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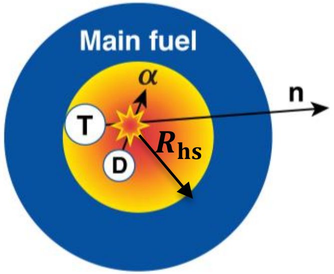
High-yield (>100 MJ) designs require an *igniting hot spot* and efficient shell confinement for burn propagation

Igniting hot spot



Ignition parameter

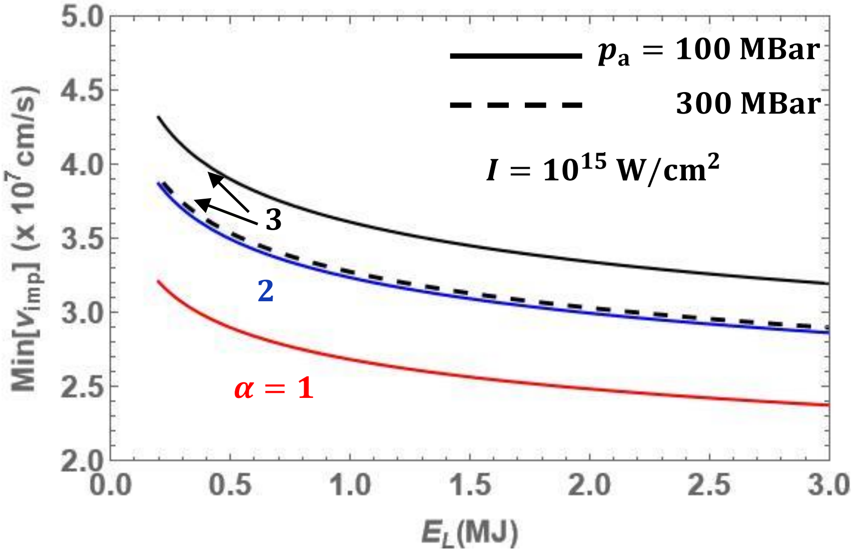
$$P_{hs}R_{hs} > 1\ \text{Gbar} \times \text{cm},\ T_i > 4.5\ \text{keV}$$

Scaling laws

$$P_{hs}R_{hs} \sim \left(\frac{p_a^{\frac{1}{3}} v_{imp}^{\frac{10}{3}}}{\alpha}\right)\left(\frac{\alpha^{\frac{1}{5}}}{p_a^{\frac{1}{15}}}\left(\frac{E_L}{v_{imp} I}\right)^{\frac{1}{3}}\right) > (PR)_{min}$$

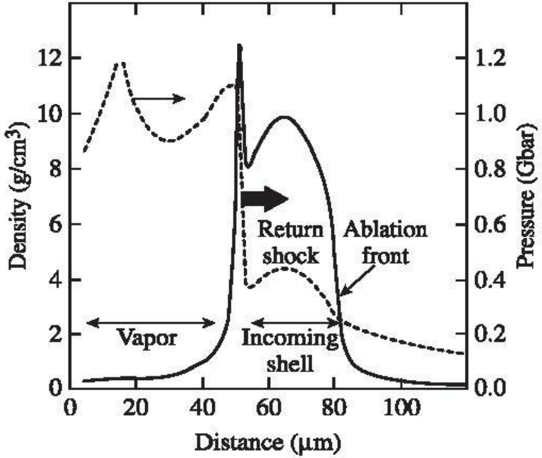
$$v_{min} \sim \frac{\alpha^{0.3}}{p_a^{0.1}}\left(\frac{I}{E_L}\right)^{0.1}$$

Shell velocity required for an igniting hot spot



High-yield designs require an igniting hot spot and *efficient shell confinement* for burn propagation

Shell confinement is limited to return shock propagation time



The return shock must be inside the shell at ignition:

$$M_{\text{shocked}}/M_{\text{DT}} \sim v_{\text{imp}}^{\frac{4}{3}} \alpha^{-\frac{2}{5}} p_{\text{a}}^{-\frac{13}{15}} < 0.5 \rightarrow$$

$$\boldsymbol{v_{\text{max}} \sim \alpha^{0.3} p_{\text{a}}^{0.65}}$$

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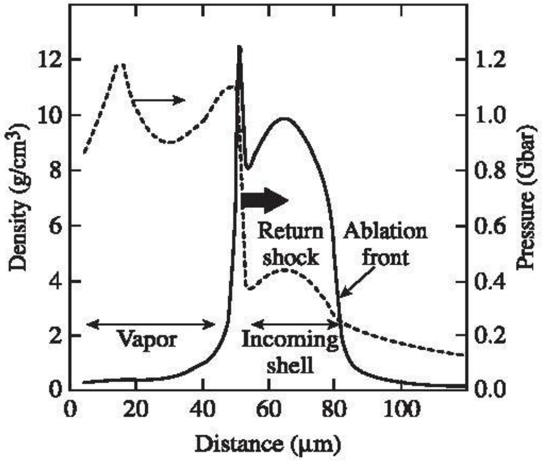
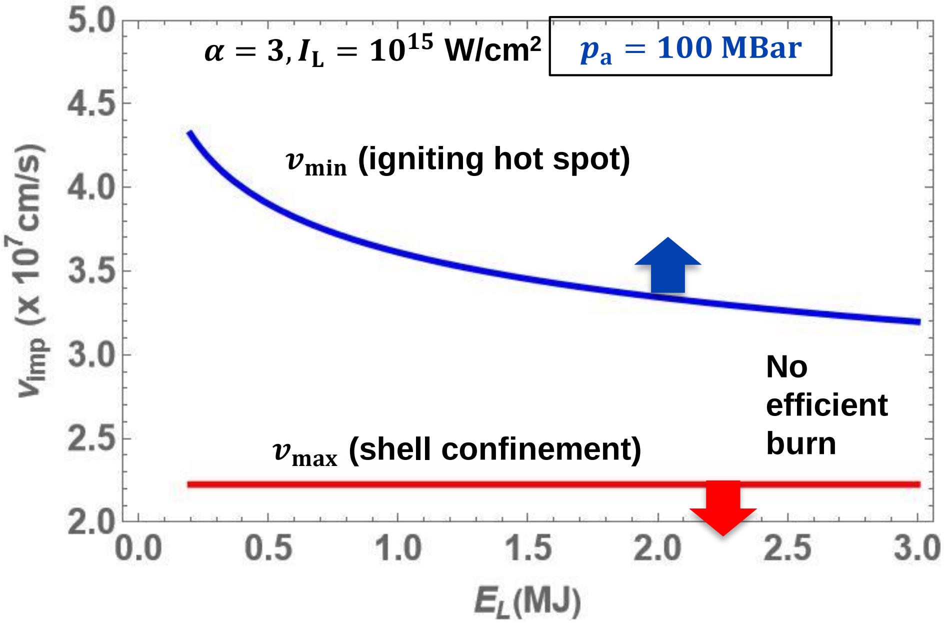


To form hot spot $\frac{\alpha^{0.3}}{p_a^{0.1}}\left(\frac{I}{E_L}\right)^{0.1} < v_{imp} < \alpha^{0.3} p_a{}^{0.65}$ For efficient burn



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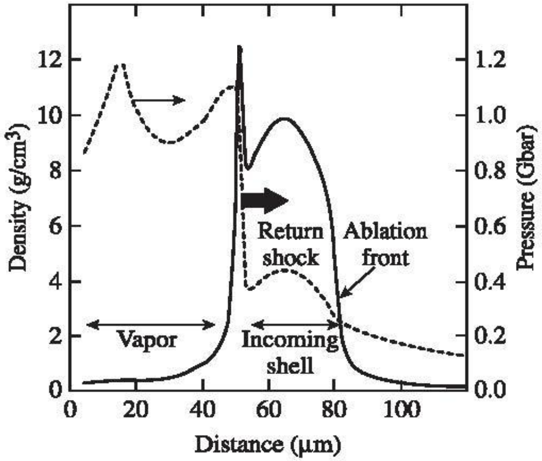

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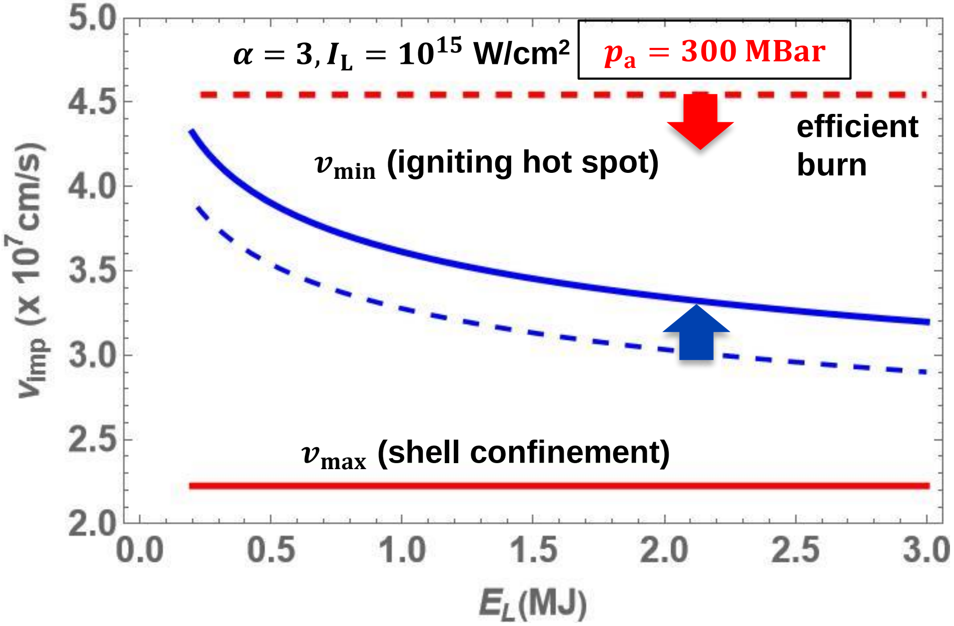
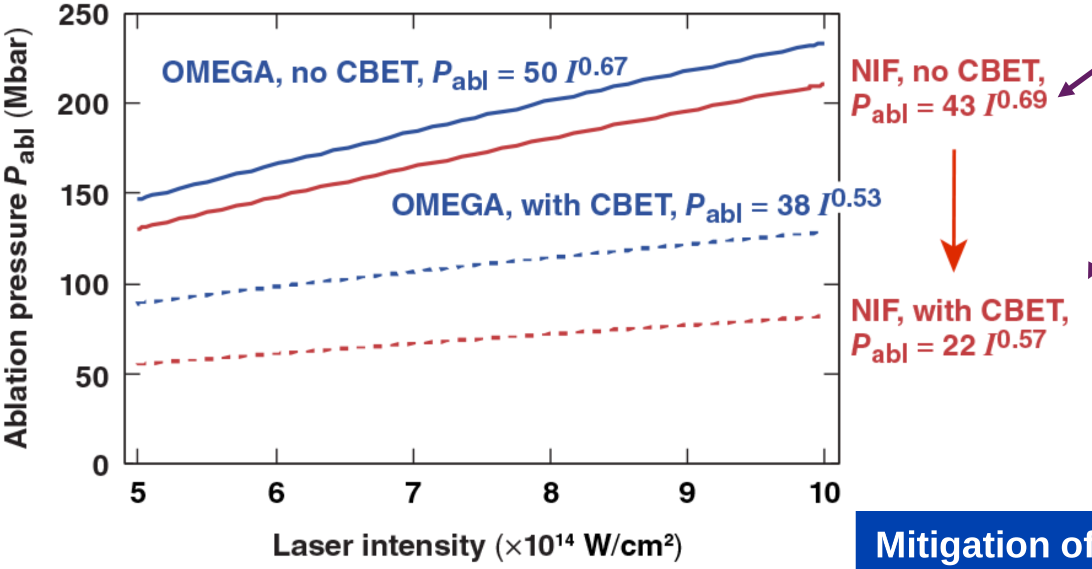


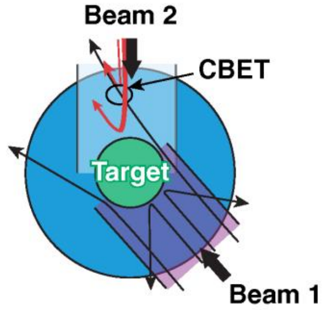
Ablation pressure in current LDD experiments is limited by laser–plasma instabilities, mainly cross-beam energy transfer (CBET)

Direct drive, $\lambda_L = 351$ nm



Bremsstrahlung absorption

Bremsstrahlung + CBET losses



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

Mitigating CBET losses creates conditions for $Y_n \sim 100$ MJ at $\alpha \sim 1$ and $E_\mathrm{L} \sim 1$ MJ

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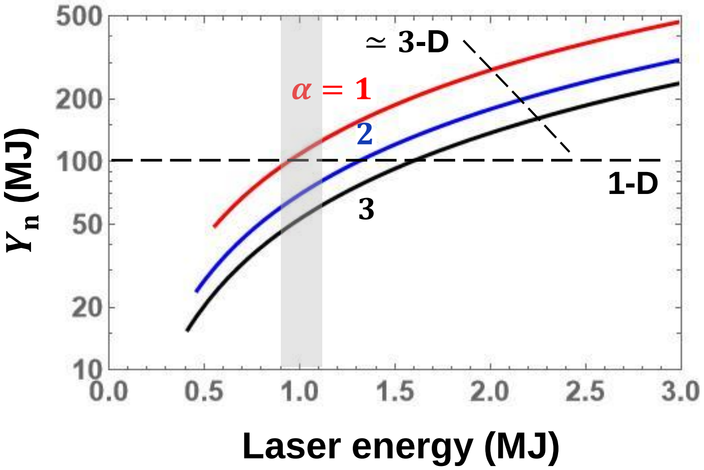
Burn fraction depends on ρR

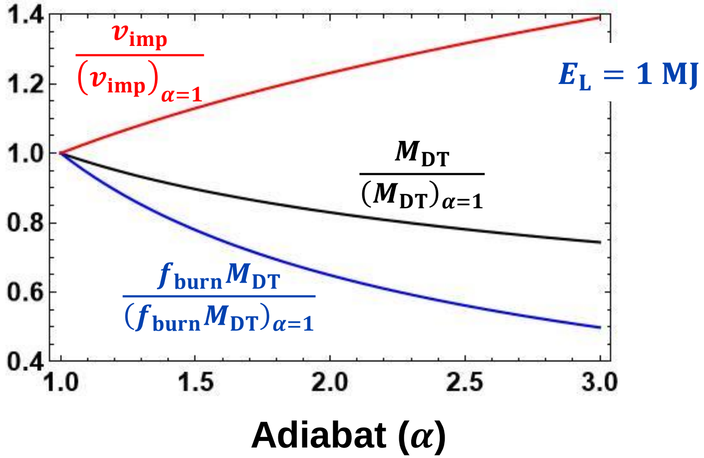
$$Y \sim f_\mathrm{burn} M_\mathrm{DT}$$

Rocket equation: $M_\mathrm{DT}\left(\frac{v_\mathrm{imp}}{t_\mathrm{accel}}\right) \sim p_\mathrm{a} R_\mathrm{shell}^2 \rightarrow M_\mathrm{DT} \sim \frac{p_\mathrm{a}}{v_\mathrm{imp}}\left(\frac{E_\mathrm{L}}{I}\right)$

$p_\mathrm{a} = 220$ MBar, $I = 10^{15}$ W/cm²



Formation of an igniting hot spot at higher adiabat requires larger v_{imp} → smaller M_{DT}



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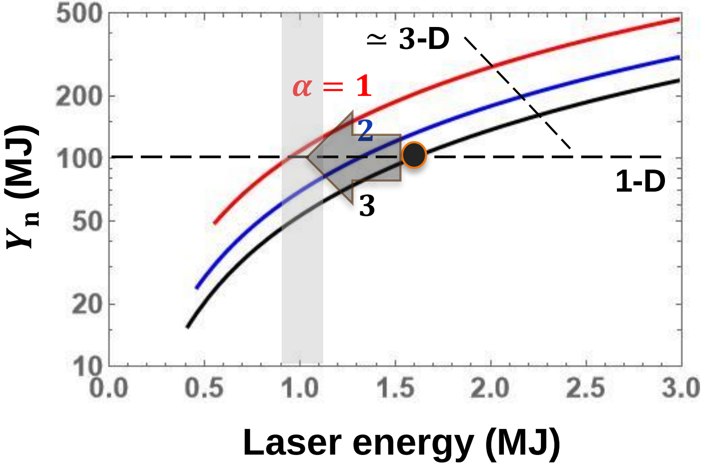

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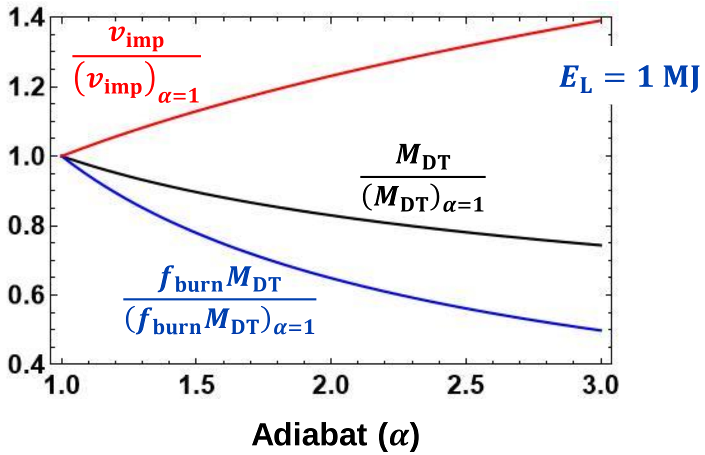

Can the laser energy of $\alpha = 3$ design be reduced?

Increasing ablation pressures improves hydrodynamic stability and reduces the laser energy required for high yields

Maximize target yield → **Increase fuel mass**

$$M_{\mathrm{DT}} \sim \frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}}\left(\frac{E_{\mathrm{L}}}{I}\right)$$

Strategy for increasing M_{DT}:

- **Reduce laser intensity**
  - Limitations:
    - reduction in v_{imp} required for efficient confinement $v_{\mathrm{max}} \sim \alpha^{0.3} {p_{\mathrm{a}}}^{0.65}$
    - higher IFAR $\left(R \sim I^{-\frac{1}{3}}\right)$
- **Increase ablation pressure**
  - Several options:
    - zooming (laser focal spot reduction through an implosion, C_{p} is higher)
    - increased I early in the pulse

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Strategy for increasing M_{DT}:

- **Reduce laser intensity** $p_{\mathrm{a}} \sim C_{\mathrm{p}}\, I^{n}$, $n = 0.7 - 0.8 \rightarrow M_{\mathrm{DT}} \sim I^{-0.25}$

  Depends on beam size, ablator material

  - Limitations:
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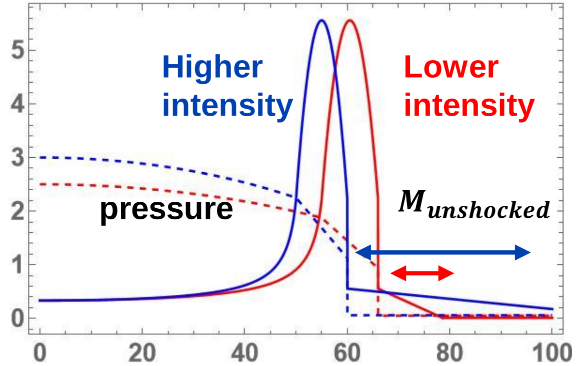
$$v_{\max} \sim \alpha^{0.3} p_{\mathrm{a}}^{0.65}$$

$$M_{shocked}/M_{DT} \sim v_{imp}^{\frac{4}{3}} \alpha^{-\frac{2}{5}} p_{a}^{-\frac{13}{15}}$$

Shock is closer to outer surface



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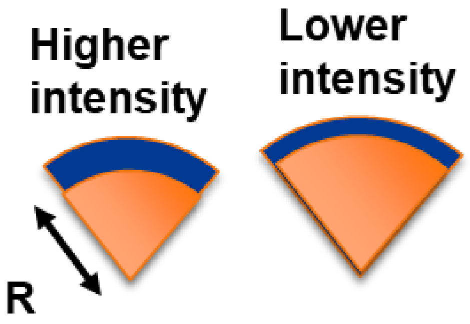
    - **higher IFAR** $\left(R \sim I^{-\frac{1}{3}}\right)$ $\quad \mathrm{IFAR} \sim \dfrac{v_{\mathrm{imp}}^{2}}{p_{\mathrm{a}}^{\frac{2}{5}} \alpha^{\frac{3}{5}}}$

Minimum velocity for ignition

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

Reduction in I and p_a leads to higher IFAR

$$\mathrm{IFAR} \sim \left(\frac{I}{E}\right)^{0.22} p_{\mathrm{a}}^{-0.58}$$



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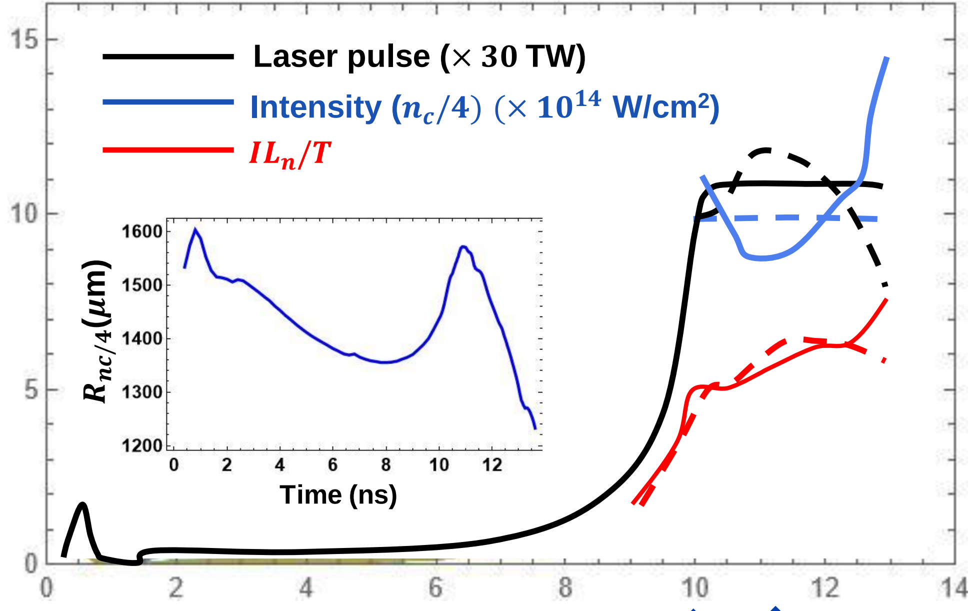
Increasing ablation pressure by zooming and early-time intensity increase allows $\alpha = 3$ LDD designs to achieve $Y_n \simeq 100$ MJ at $E_L \sim 1$ MJ

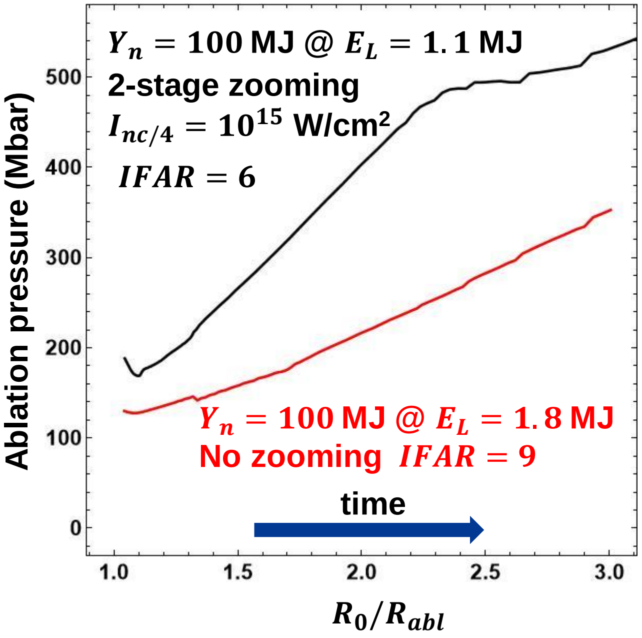
2 designs with the same M_{DT} and v_{imp}



Time (ns)

Zooming 1: $R_b/R_{b0} = 0.55$ **Zooming 2: $R_b/R_{b0} = 0.4$**

$\alpha = 3$ design



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