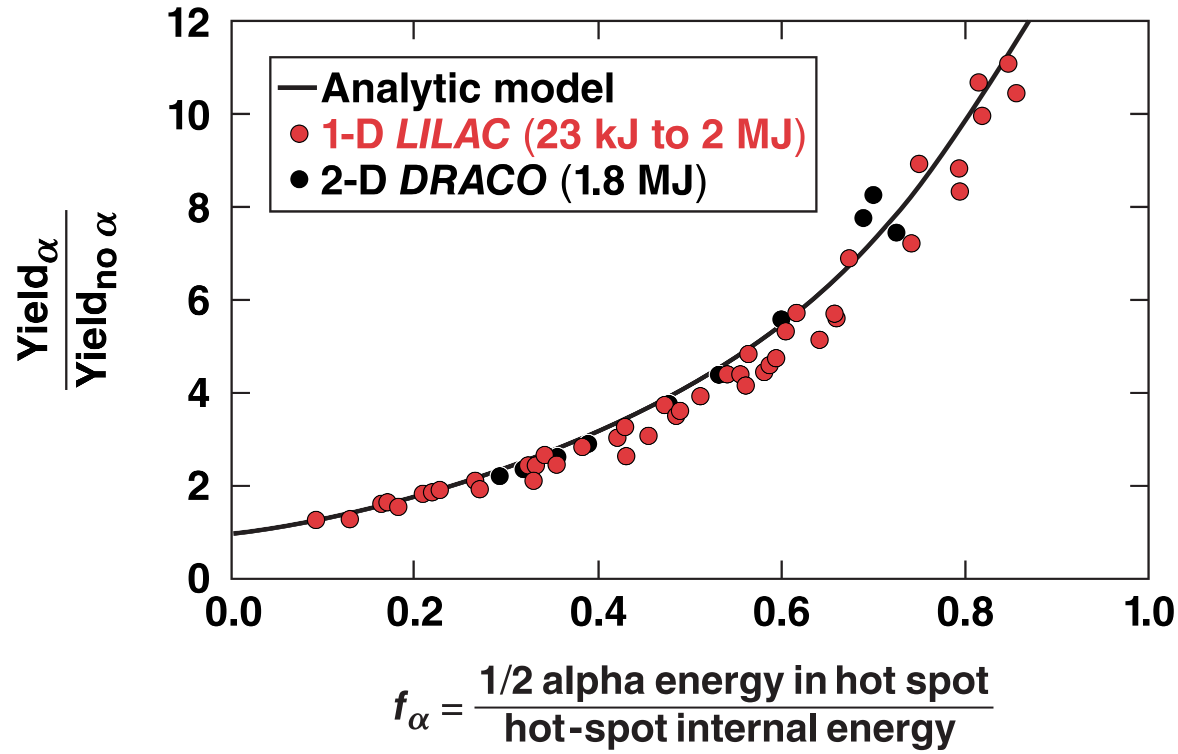
Measurements of Alpha Heating in Inertial Confinement Fusion



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Summary

Measurements of alpha heating are developed and used to determine the yield amplification caused by alphas and the requirements for ignition

- Alpha heating is estimated in two different ways using the Lawson parameter and the fractional alpha energy
- National Ignition Facility (NIF) shot N140120 exhibits an ~2.5× amplification of the neutron yield caused by alpha heating and a no-burn Lawson parameter of ~0.65
- Options for ignition: higher in-flight aspect ratios (IFAR's), improved yield-over-clean (YOC), and/or use of adiabat shaping

Collaborators

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Hot-spot evolution (including alpha heating) depends almost exclusively on the Lawson ignition parameter

- The model solves the mass, momentum, and energy conservation equations for the hot-spot pressure $\hat{P}$, temperature $\hat{T}$, and radius $\hat{R}$*

- Energy conservation: $\frac{d}{d\tau}\left(\hat{P}\hat{R}^5\right) = \gamma \hat{P}^2 \hat{R}^5 \hat{T} - \beta \hat{P}^2 \hat{R}^5 \hat{T}^{-5/2}$

  Alpha heating ($\gamma \hat{P}^2 \hat{R}^5 \hat{T}$)   Radiation losses ($\beta \hat{P}^2 \hat{R}^5 \hat{T}^{-5/2}$)

- The solution is singular when $\chi_{\text{no}\,\alpha} = \left[\frac{P\tau}{(P\tau)_{\text{ign}}}\right]_{\text{no}\,\alpha} \equiv \underbrace{\frac{\gamma}{1.11+0.7\,\beta}}_{\text{Lawson parameter}}$

- Rewrite energy equation dependent approximately only on $\chi_{\text{no}\,\alpha}$

$$\frac{d}{d\tau}\left(\hat{P}\hat{R}^5\right) = 1.1\,\chi_{\text{no}\,\alpha}\,\hat{P}\hat{R}^5\hat{T} + \hat{P}^2\hat{R}^5\left(0.7\,\chi_{\text{no}\,\alpha}\,\beta\hat{T} - \beta\hat{T}^{-5/2}\right)$$

Quasi cancellation (~20% error)

*C. D. Zhou and R. Betti, Phys. Plasmas 15, 102707 (2008);
P.-Y. Chang *et al*., Phys. Rev. Lett. 104, 135002 (2010);
R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

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$\chi_{\text{no}\,\alpha}$ is the most useful ignition metric, but only χ_{α} can be measured

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- The no-α ignition parameter is written in terms of the yield (Y) and ρR

$$\chi_{\text{no}\,\alpha} = (\rho R_{\text{no}\,\alpha})^{0.61}\left(0.24\frac{Y_{\text{no}\,\alpha}}{M^{\text{DT}}}\right)^{0.34}$$

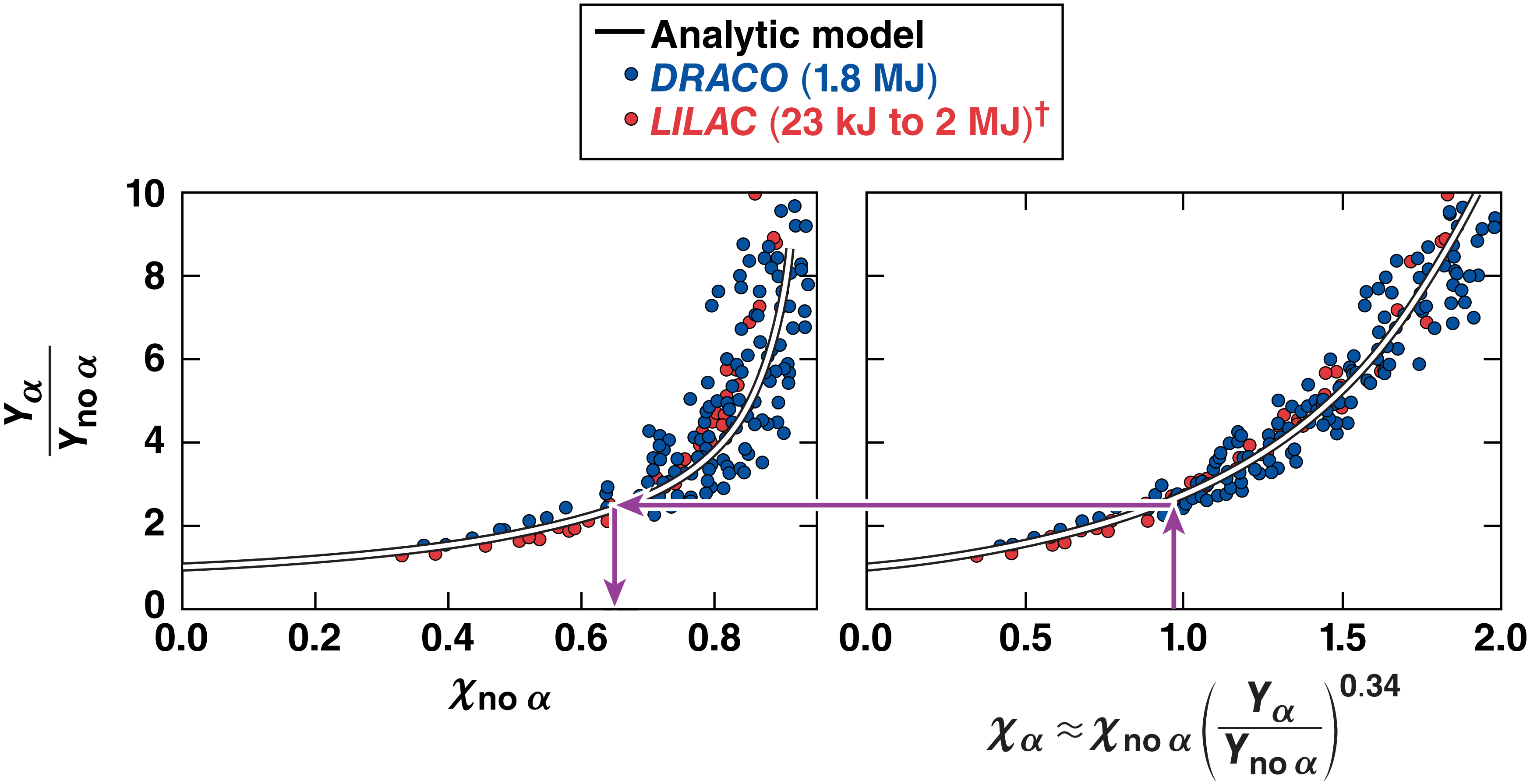
- The measureable parameter must use quantities with alpha heating

$$\chi_{\alpha} = (\rho R_{\alpha})^{0.61}\left(0.24\frac{Y_{\alpha}}{M^{\text{DT}}}\right)^{0.34} \approx \chi_{\text{no}\,\alpha}\left(\frac{Y_{\alpha}}{Y_{\text{no}\,\alpha}}\right)^{0.34}$$

- ρR = total areal density in g/cm^2
- Y = neutron yield in units of 10^{16} neutrons
- M^{DT} = unablated DT mass in mg

R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

The yield-enhancement curves are used to measure both the yield enhancement caused by alphas and the no-alpha Lawson parameter



*In general agreement with B. Spears' (LLNL) simulation results for NIF-ID point design target:
B. Spears and J. Lindl, "Ignition Metrics and Their Role in Setting Specifications and Evaluating Progress Toward Ignition on the NIF," LLNL, Livermore, CA, UCRL report under review (2014).; P. Patel *et al*., Bull. Am. Phys. Soc. 58, 193 (2013).

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Another way of inferring alpha heating is through the fractional alpha energy deposited in the hot spot

$$f_\alpha \equiv \frac{0.5\, E_\alpha^{\mathrm{abs}}}{\frac{3}{2}\langle P\rangle V_{\mathrm{hs}}}$$

- $E_\alpha^{\mathrm{abs}} = \theta_\alpha \times$ Yield $\times$ 3.5 MeV = absorbed alpha energy in the hot spot

- $\theta_\alpha \approx 0.9\left(1 - \frac{1}{3.4\,\tau} + \frac{1}{160\,\tau^2}\right)$ = fraction of alphas absorbed in the hot spot*

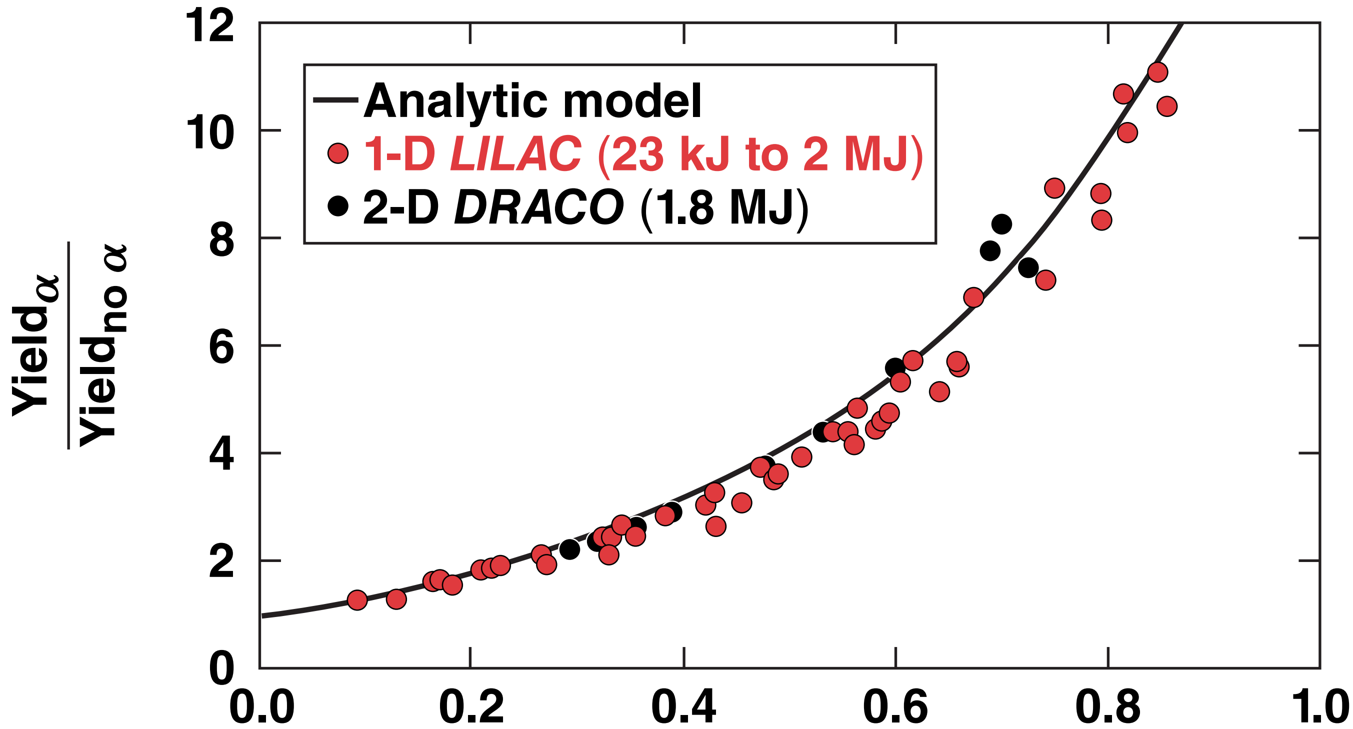
  where $\tau = \frac{\text{hot-spot radius}}{\text{alpha-particle range}} = \left(\frac{P_{\mathrm{Gbar}}}{100}\right)\left(\frac{R_{\mu\mathrm{m}}}{50}\right)\left(\frac{5}{T_{\mathrm{keV}}}\right)^{5/2}$

- Pressure and volume are inferred from observables according to C. Cerjan *et al.***

f_α can be directly inferred from experimental observables.

* O. N. Krokhin and V. B. Rozanov, Sov. J. Quantum Electron. 2, 393 (1973).
**C. Cerjan, P. T. Springer, and S. M. Sepke, Phys. Plasmas 20, 056319 (2013).

The yield enhancement is an almost unique function of the fractional alpha energy f_α



$$f_\alpha = \frac{1/2\ \alpha\text{-energy deposited in hot spot}}{\text{hot-spot internal energy}}$$

Alpha-heating analysis of NIF high-foot (HF) shot N140120

- Yield = 9.2×10^{15}, ρR = 0.8 g/cm^2, M_{DT} = 0.18 mg, burnwidth = 161 ps, T = 4.9 keV, and R_{hs} = 35.2 μm*
- The χ_α analysis gives $\chi_\alpha \approx 1$, a yield amplification of 2.5, and $\chi_{no\ \alpha} = 0.65$
- The f_α analysis gives $f_\alpha \approx 0.38$, a yield amplification of 2.7, and $\chi_{no\ \alpha} = 0.67$

Both the χ_α and the f_α analyses give similar results.

*P. K. Patel, Lawrence Livermore National Laboratory, private communication (2014); O. A. Hurricane and H. S. Park, presented at the IDI Web Meeting, February 2014.

Options for ignition: higher IFAR, improved YOC, and/or use of adiabat shaping

$$\chi_{\text{no } \alpha} \sim \theta_{\alpha} E_{\text{kin}}^{0.37} \text{YOC}^{0.4} P_{\text{abl}}^{0.4 \text{ to } 0.6} \text{IFAR } S_{\text{adiabat}}^{0.6}$$

- θ_{α} fraction of absorbed alphas $\approx$ 0.7
- S_{adiabat} = adiabat shaping factor = $\langle \alpha \rangle / \alpha_{\text{inner}}$
- Best shot to date → $\chi_{\text{HF}} \approx 0.65$ (χ = 1 for ignition)
- Options for achieving ignition
  – improve YOC (shape, IFAR, S_{adiabat}) but YOC is already high
  – increase θ_{α} (compressed B field at 0.5 Gauss?)*
  – increase IFAR (but YOC may go down)
  – use adiabat shaping → increase S_{adiabat}

*L. J. Perkins *et al*., Phys. Plasmas 20, 072708 (2013);
G. Logan, Lawrence Berkeley National Laboratory, private communication (2014).

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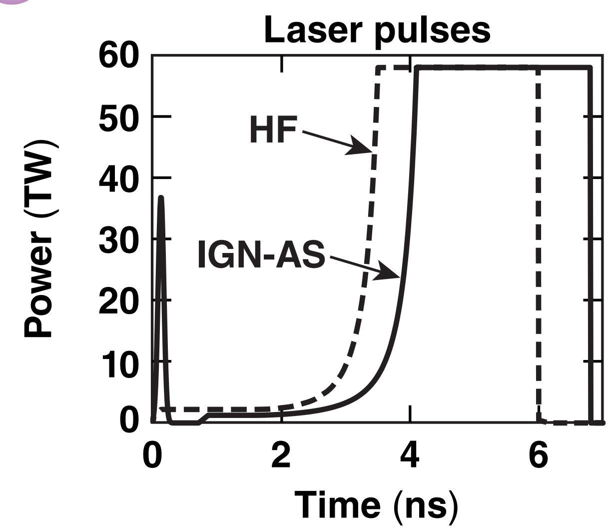
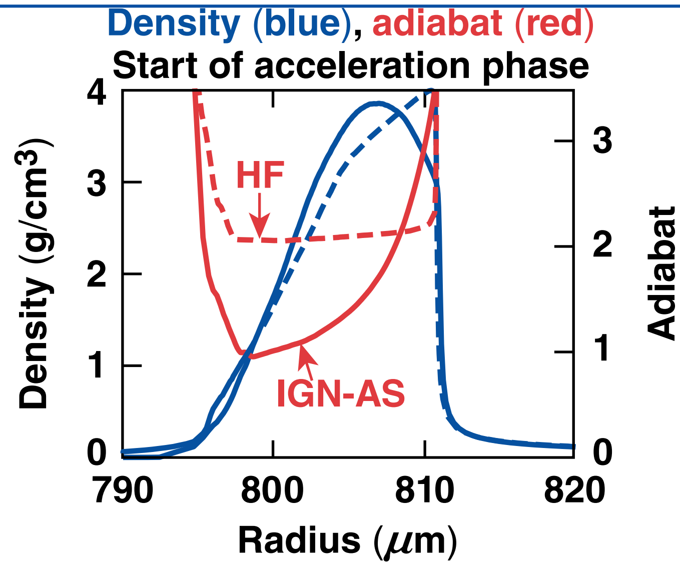
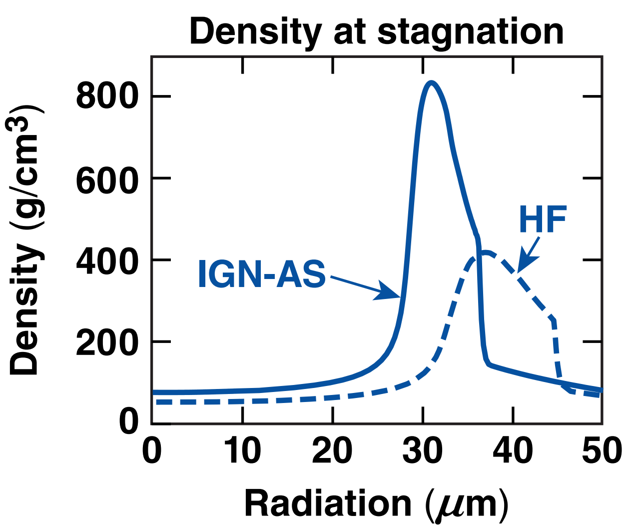
Direct-drive simulations of the high foot (HF) show a possible ignition path with adiabat shaping (AS) and modest IFAR, CR, and pulse-length increase







- Ignition pulse with AS is 13% longer
- IFAR at 2/3 radius is 20% higher in ignition pulse with AS
- Expected similar ablation-front growth factors
- Convergence ratio (CR) is 15% higher in ignition pulse with AS

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