Measurements of Alpha Heating in Inertial Confinement Fusion

![Graph showing yield vs. alpha energy fraction]

- **Analytic model**
- **1-D LILAC (23 kJ to 2 MJ)**
- **2-D DRACO (1.8 MJ)**

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

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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 $\sim 2.5 \times$ amplification of the neutron yield caused by alpha heating and a no-burn Lawson parameter of $\sim 0.65$
- Options for ignition: higher in-flight aspect ratios (IFAR’s), improved yield-over-clean (YOC), and/or use of adiabat shaping
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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 $P_t$, temperature $T_t$, and radius $R_t^*$

  - Energy conservation: \[
  \frac{d}{d\tau}(\dot{P}R^5) = \gamma\dot{P}^2R^5\dot{T} - \beta\dot{P}^2R^5\dot{T}^{-5/2}
  \]

  - Alpha heating
  - Radiation losses

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

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

  \[
  \frac{d}{d\tau}(\dot{P}R^5) = 1.1\chi_{no} \gamma\dot{P}^2R^5\dot{T} + \dot{P}^2R^5(0.7\chi_{no}\beta\dot{T} - \beta\dot{T}^{-5/2})
  \]

  Quasi cancellation (~20% error)

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

- The no-$\alpha$ ignition parameter is written in terms of the yield ($Y$) and $\rho R$

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

- The measureable parameter must use quantities with alpha heating

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

- $\rho R =$ total areal density in g/cm$^2$
- $Y =$ neutron yield in units of $10^{16}$ neutrons
- $M_{\text{DT}} =$ unablated DT mass in mg

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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:

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

\[ f_\alpha \equiv \frac{0.5 E^\text{abs}_\alpha}{\frac{3}{2} \langle P \rangle V_{\text{hs}}} \]

- \( E^\text{abs}_\alpha = \theta_\alpha \times \text{Yield} \times 3.5 \text{ MeV} \) = 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 \( \tau = \frac{\text{hot-spot radius}}{\text{alpha-particle range}} = \left( \frac{P_{\text{Gbar}}}{100} \right) \left( \frac{R_{\mu\text{m}}}{50} \right) \left( \frac{5}{T_{\text{keV}}} \right)^{5/2} \)

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

\[ f_\alpha \text{ can be directly inferred from experimental observables.} \]

The yield enhancement is an almost unique function of the fractional alpha energy $f_{\alpha}$.

$$f_{\alpha} = \frac{1/2 \text{ } \alpha\text{-energy deposited in hot spot}}{\text{hot-spot internal energy}}$$
Alpha-heating analysis of NIF high-foot (HF) shot N140120

- Yield = \(9.2 \times 10^{15}\), \(\rho R = 0.8\) g/cm\(^2\), \(M_{DT} = 0.18\) mg, burnwidth = 161 ps, \(T = 4.9\) keV, and \(R_{hs} = 35.2\) \(\mu\)m*

- The \(\chi_\alpha\) analysis gives \(\chi_\alpha \approx 1\), a yield amplification of 2.5, and \(\chi_{no\alpha} = 0.65\)

- The \(f_\alpha\) analysis gives \(f_\alpha \approx 0.38\), a yield amplification of 2.7, and \(\chi_{no\alpha} = 0.67\)

Both the \(\chi_\alpha\) and the \(f_\alpha\) analyses give similar results.

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

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

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

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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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