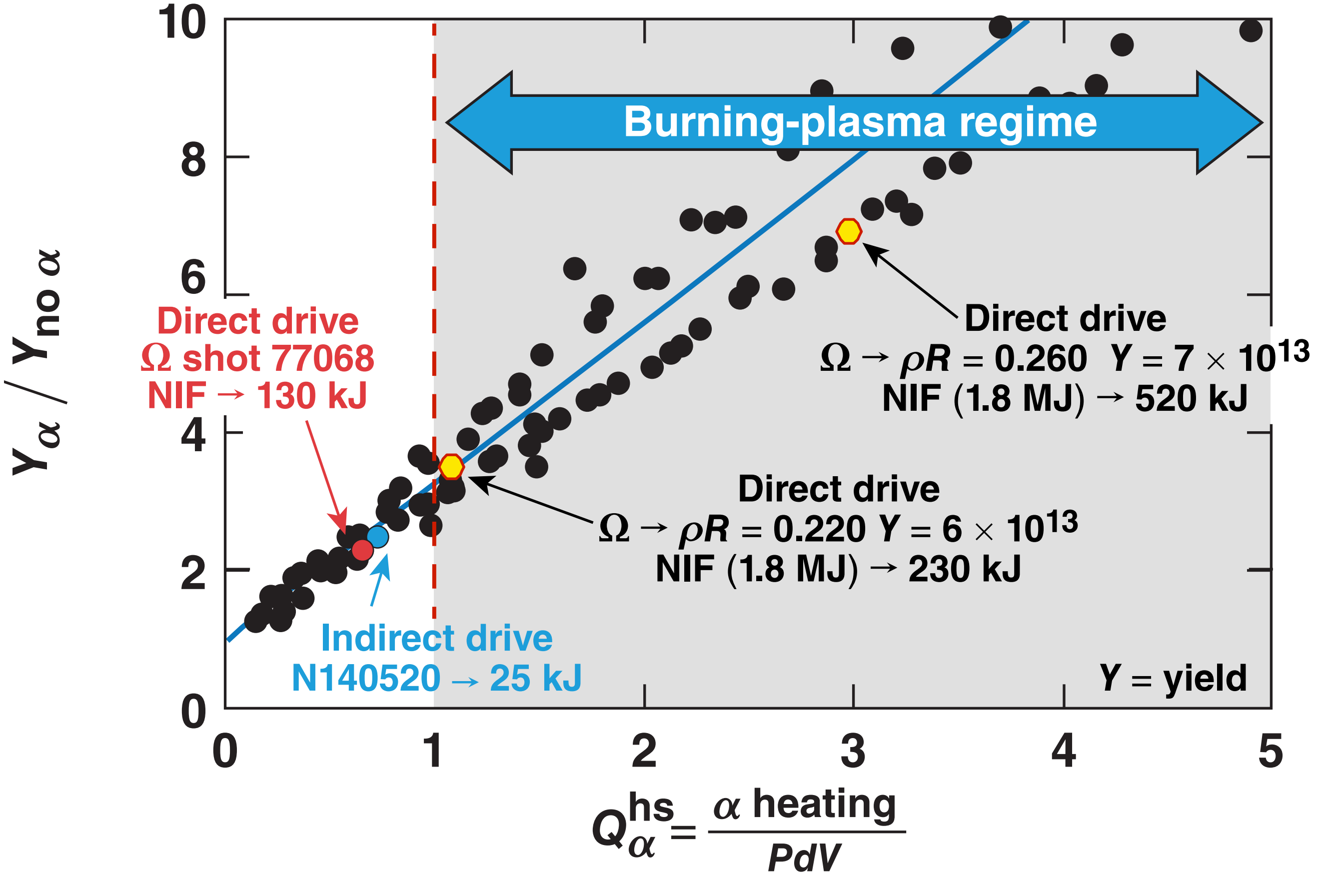
The Most Unsolved Problem in Plasma Physics: Demonstrating a Burning Plasma in the Laboratory



Direct drive
Ω shot 77068
NIF → 130 kJ

Indirect drive
N140520 → 25 kJ

Direct drive
Ω → ρR = 0.220 $Y = 6 \times 10^{13}$
NIF (1.8 MJ) → 230 kJ

Direct drive
Ω → ρR = 0.260 $Y = 7 \times 10^{13}$
NIF (1.8 MJ) → 520 kJ

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Solved and Unsolved
Problems in Plasma Physics
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The onset of the burning-plasma regime can be identified through experimental observables related to the yield amplification from alpha heating

- The fundamental parameter characterizing burning plasmas is $Q_\alpha = \text{alpha heating} / PdV$ work
- Current high-foot* implosions at the National Ignition Facility (NIF) have achieved Q_α^{hs} = 0.5 - 0.6 with a yield amplification caused by alpha heating of about 2.5×
- For a high-foot-like* target, the onset of the burning-plasma regime in the hot spot $(Q_\alpha^{hs} = 1)$ requires ~50 kJ of fusion energy
- Hydro-equivalent** extrapolations of direct-drive OMEGA implosions to 1.8-MJ symmetric illumination indicate performance similar to indirect drive

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*O. A. Hurricane *et al.*, Nature 506, 343 (2014);

**R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

Collaborators

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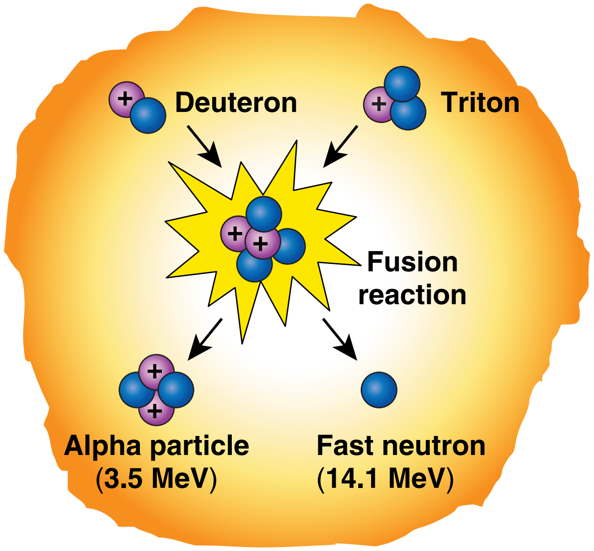
The simplest α-heating model assumes that fusion reactions start after the plasma stagnates

DT fusion plasma (hot spot)

$$P(0) = P_{\text{no } \alpha}$$



Time-dependent energy balance

Fusion reactivity

$$\frac{d}{dt}\left(\frac{3}{2}P\right) = \frac{n^2}{4}\langle\sigma v\rangle\,\varepsilon_\alpha - \frac{3}{2}\frac{P}{\tau} \qquad P(0) = P_{\text{no } \alpha}$$

$P \approx 2nT$ 3.5 MeV Confinement time

The plasma is brought to a pressure $P_{\text{no } \alpha}$ using only a spherical piston (the imploding shell).

The dimensionless form of the energy balance depends only on the no-α Lawson* parameter

- Assume $\langle \sigma v \rangle \sim T^2$

Set $\hat{P} \equiv \dfrac{P}{P_{\text{no}\,\alpha}}$ $\quad \hat{t} \equiv \dfrac{t}{\tau}$ $\quad \hat{P}(0) \equiv 1$

$$\boxed{\frac{d\hat{P}}{d\hat{t}} = \hat{P}\left(\chi_{\text{no}\,\alpha}\hat{P} - 1\right)}$$

Without α heating ⟶ $\boxed{\dfrac{d\hat{P}}{d\hat{t}} = -\hat{P}}$

No-α Lawson parameter

$$\boxed{\chi_{\text{no}\,\alpha} \equiv \frac{P_{\text{no}\,\alpha}\,\tau}{S_\alpha}}$$

$$\boxed{S_\alpha \equiv \frac{24T^2}{\varepsilon_\alpha \langle \sigma v \rangle} = \left(P_{\text{no}\,\alpha}\tau\right)_{\text{ign}}^{\text{min}}}$$

Note: S_α has the dimensions of $P\tau$

TC12268a

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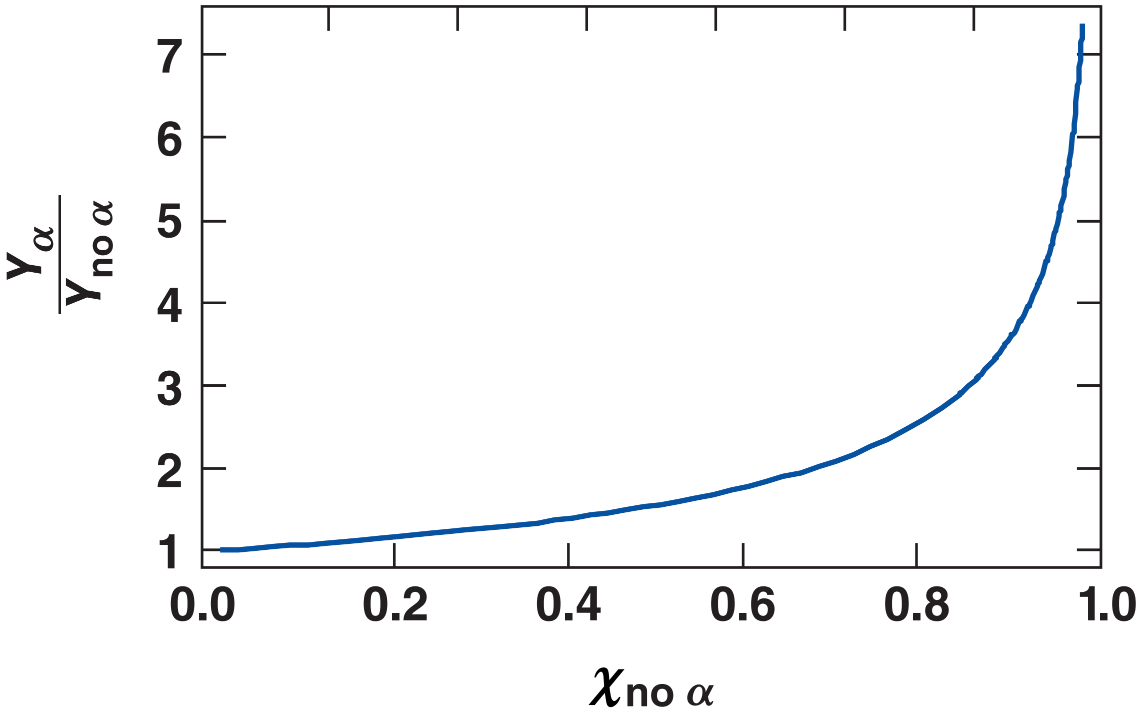
*J. D. Lawson, Proc. Phys. Soc. Lond. B 70, 6 (1957).

The amplification of the yield caused by alpha heating is a unique function of the no-α Lawson parameter

$$\frac{Y_{\alpha}}{Y_{\text{no}\,\alpha}} = \frac{2}{\chi_{\text{no}\,\alpha}^{2}}\left[\ln\left(\frac{1}{1-\chi_{\text{no}\,\alpha}}\right) - \chi_{\text{no}\,\alpha}\right] \qquad \chi_{\text{no}\,\alpha} \equiv \frac{P_{\text{no}\,\alpha}\tau}{\left(P_{\text{no}\,\alpha}\tau\right)_{\text{ign}}^{\text{min}}}$$



TC12271

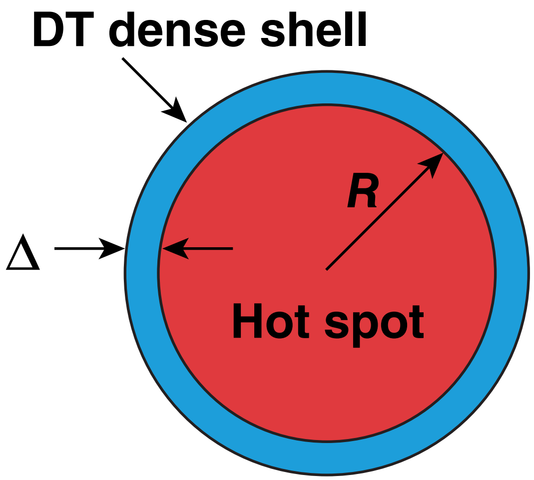
Generalized in 3-D in P.-Y. Chang *et al*., Phys. Rev. Lett. 104, 135002 (2010).

The scaling of the no-α Lawson parameter follows that of the ignition threshold factor* (ITFx)

Newton's law of the dense shell confining the hot-spot pressure**

$$M_{DT}^{sh}\ddot{R} = -4\pi PR^2$$

$$M_{DT}^{sh}\frac{R}{\tau^2} \sim PR^2 \Longrightarrow \tau \sim \sqrt{\frac{M_{DT}^{sh}}{PR}}$$



Approximate total areal density ρR

Shell mass

$$M_{DT} \sim (\rho_{shell}\Delta)R^2 \qquad Y \sim P^2\tau V$$

Same as LLNL ITFx, with ρR replaced by the down-scatter ratio (DSR)*

$$\boxed{\chi^3 \sim \frac{Y}{M_{DT}^{sh}}(\rho R)^2}$$

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*B. K. Spears *et al.*, Phys. Plasmas 19, 056316 (2012).
**R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

The amplification of the yield caused by α heating is also a unique function of the Lawson parameter with α

$\chi_{\text{no}\,\alpha}$ cannot be measured

$$\chi_{\text{no}\,\alpha} \sim Y_{\text{no}\,\alpha}^{1/3}$$

χ_{α} can be measured

$$\chi_{\alpha} \sim Y_{\alpha}^{1/3}$$

$$\boxed{\chi_{\text{no}\,\alpha} = \chi_{\alpha}\left(\frac{Y_{\text{no}\,\alpha}}{Y_{\alpha}}\right)^{1/3}}$$

$$\boxed{\frac{Y_{\alpha}}{Y_{\text{no}\,\alpha}} = \frac{2}{\chi_{\text{no}\,\alpha}^{2}}\left[\ln\left(\frac{1}{1-\chi_{\text{no}\,\alpha}}\right) - \chi_{\text{no}\,\alpha}\right]} \quad \Rightarrow \quad \boxed{\frac{Y_{\alpha}}{Y_{\text{no}\,\alpha}} = F(\chi_{\alpha})}$$

$$\boxed{\chi_{\alpha} \sim \left[\frac{0.24\, Y_{16}^{\alpha}}{M_{\text{DT(mg)}}^{\text{sh}}}\right]^{1/3} \left(\rho R_{\text{g/cm}^2}\right)^{2/3}}$$

← χ_{α} valid in 3-D,* although the definition of ρR is difficult; use DSR**

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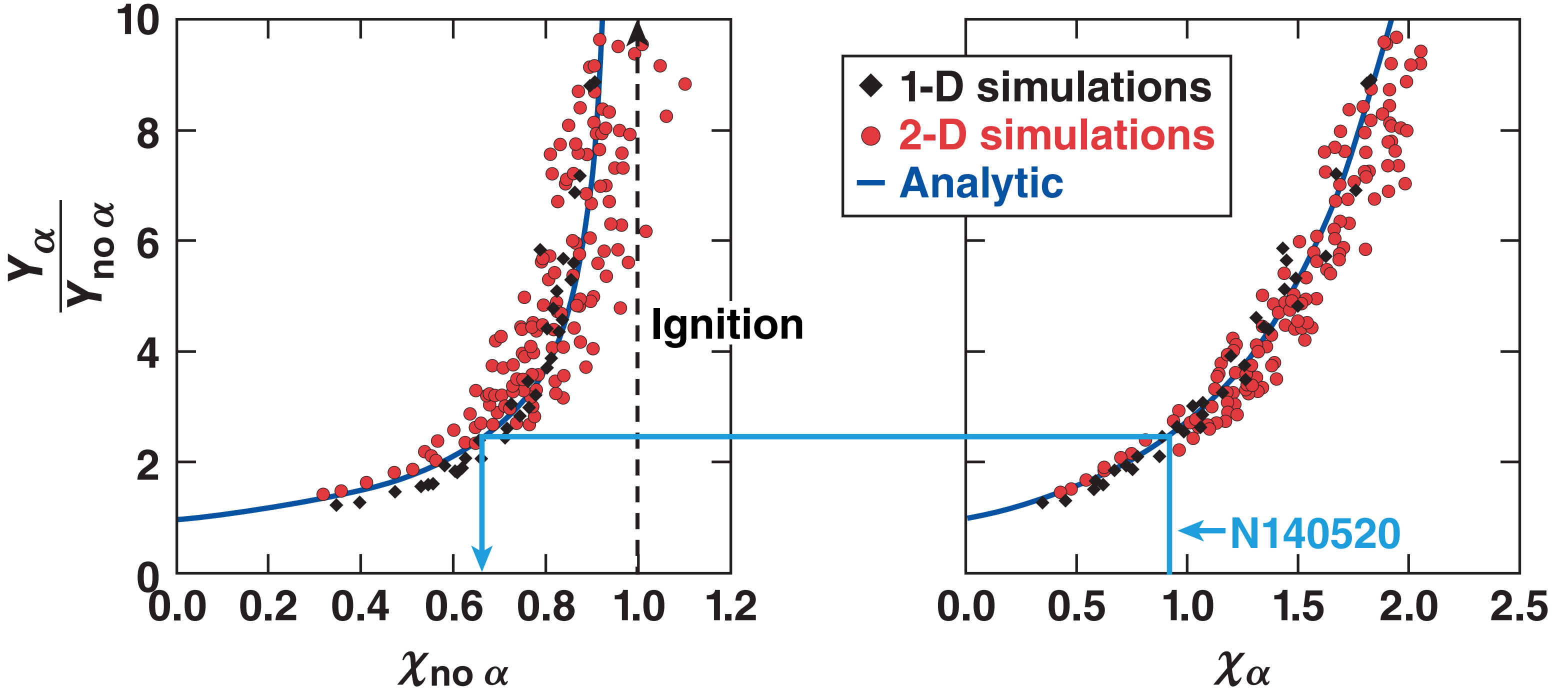
*P.-Y. Chang *et al*., Phys. Rev. Lett. 104, 135002 (2010).

**B. K. Spears *et al*., Phys. Plasmas 22, 056317 (2012).

TC12282a

In high-foot implosions, the fusion yield increased by about 2.5× because of α heating



O. A. Hurricane *et al*.,
Phys. Rev. Lett. 115,
055001 (2015).

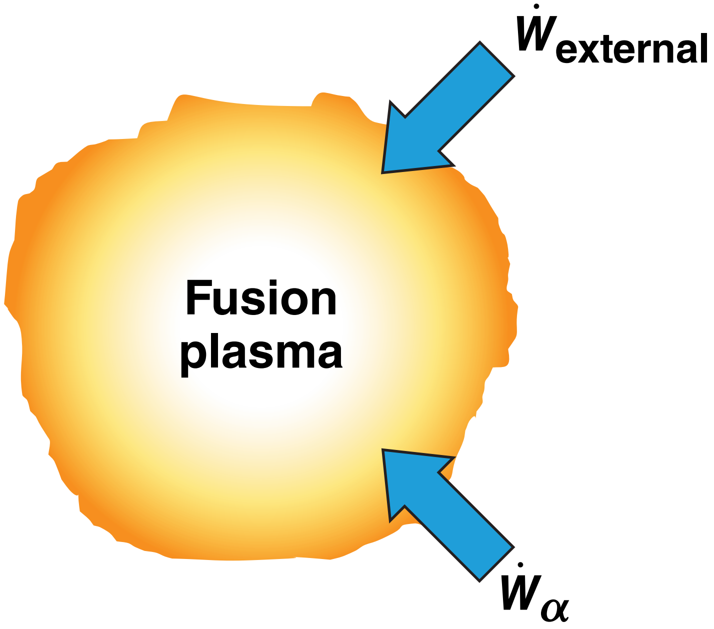
→

High-foot N140520:
$\rho R \approx 0.8$ g/cm^2,
$Y = 9 \times 10^{15}$, $M_{DT} = 0.18$ mg

$\boxed{\chi_\alpha \approx 0.95}$

Used in J. Lindl *et al*., Phys. Plasmas 21, 020501 (2014); 21, 129902(E) (2014).

In a burning plasma, the α heating is the dominant power input to the fusion plasma



$$Q_{\alpha} \equiv \frac{\dot{W}_{\alpha}}{\dot{W}_{\text{ext}}}$$

Burning plasmas
$Q_{\alpha} > 1$

Steady-state energy balance with power input

$$\underset{\text{External input}}{\longrightarrow}\; \dot{W}_{\text{ext}} + \underset{\uparrow}{C_{\alpha} P^2 V} = \frac{3}{2}\frac{P}{\tau}V \;\underset{\text{Energy losses}}{\longleftarrow}$$

$\dot{W}_{\alpha}$ = alpha heating for $\langle \sigma v \rangle \sim T^2$

TC12284a

The yield amplification caused by α heating depends exclusively on Q_α

From the power balance: pressure with α

$$\tau_{\mathrm{ICF}} \approx \frac{C_\tau}{P_\alpha^{0.5}}$$

$$Q_\alpha \equiv \frac{\dot{W}_\alpha}{\dot{W}_{\mathrm{ext}}}$$

$$P_\alpha = \left[\frac{2}{3V}\dot{W}_{\mathrm{ext}}\left(1+Q_\alpha\right)C_\tau\right]^{2/3}$$

From the power balance: pressure without α

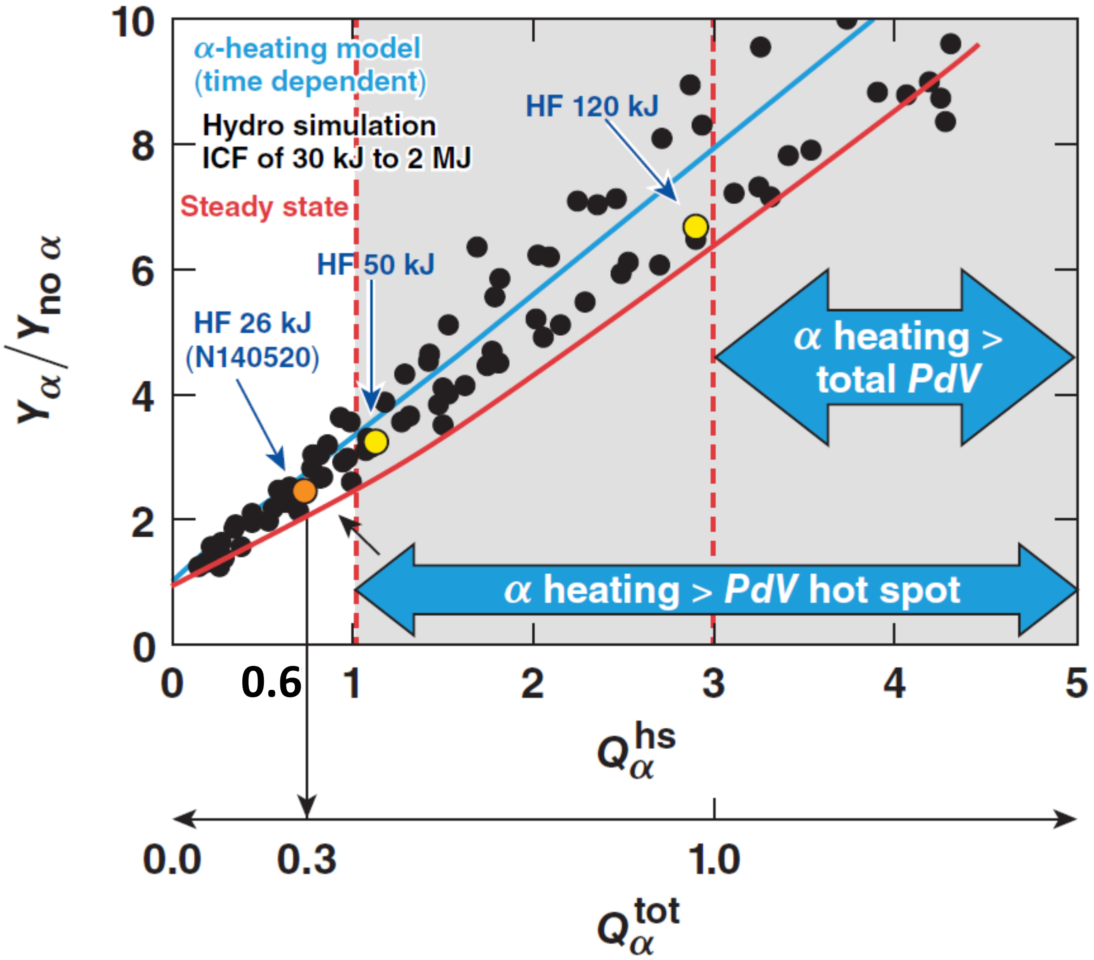
$$P_{\mathrm{no}\,\alpha} = \left[\frac{2}{3V}\dot{W}_{\mathrm{ext}}C_\tau\right]^{2/3}$$

Yield amplification is a unique function of Q_α

$$\boxed{\frac{Y_\alpha}{Y_{\mathrm{no}\,\alpha}} = \frac{P_\alpha^2}{P_{\mathrm{no}\,\alpha}^2} = \left(1+Q_\alpha\right)^{4/3}}$$

TC12286a

The onset of the hot-spot burning-plasma regime can be determined through the yield amplification



$Q_\alpha^{hs} = 1$

$Y_{amp} = 3.5\times$

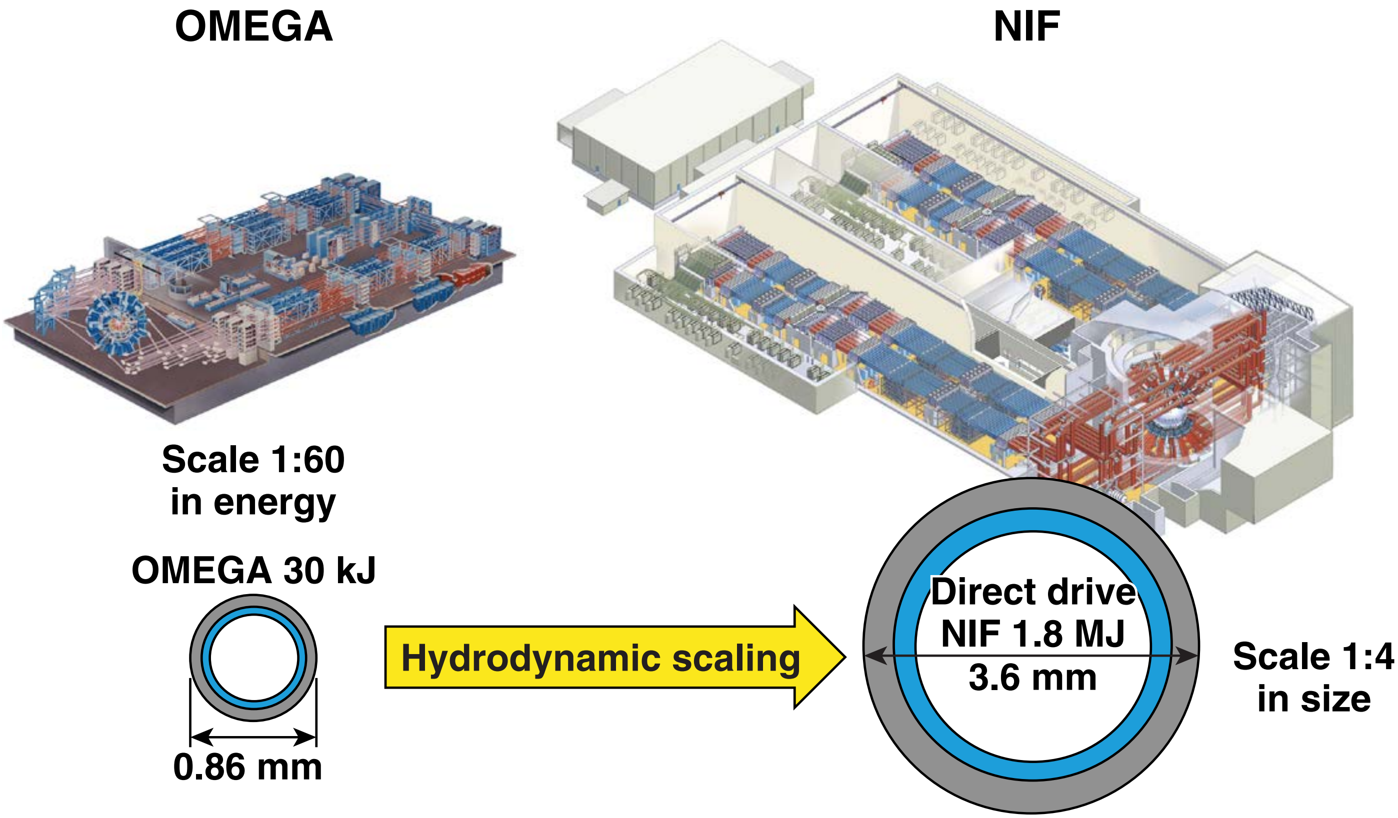
$Q_\alpha^{tot} = 1$

$Y_{amp} = 7.0\times$

R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015).

TC12297a

Hydrodynamic equivalence provides a tool to scale the performance of OMEGA direct-drive implosions to NIF energies for symmetric illumination



Hydrodynamic scaling does NOT account for differences in laser–plasma interactions between OMEGA and the NIF.

3-D theory for R. Nora *et al*., Phys. Plasmas 21, 056316 (2014).

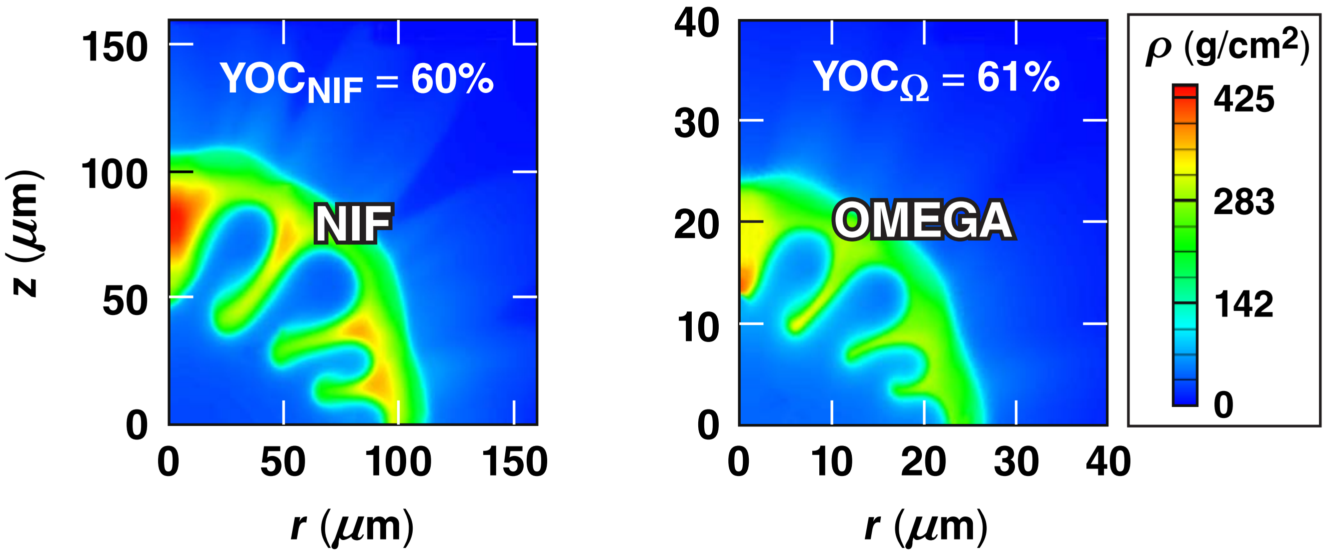
The hydrodynamic scaling holds in three dimensions

- **In-flight scaling:** $R \sim E_L^{1/3}$ $P_L \sim E_L^{2/3}$ $\tau_{pulse} \sim E_L^{1/3}$

  $V_{imp} \sim \mathrm{const}$ $\alpha \sim \mathrm{const}$ RT growth factors ~ const

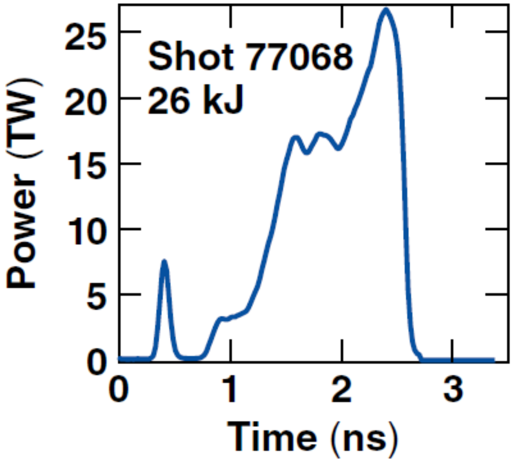
- **Stagnation scaling:** $P \sim \mathrm{const}$ $T \sim R^{0.2}$ $V_{hs} \sim R^3$

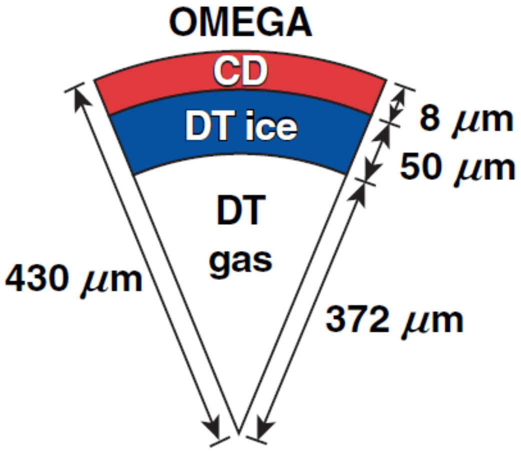
  $\tau_{burn} \sim R$ $\rho R_{tot} \sim R$



A. Bose *et al.*, Phys. Plasmas 22, 072702 (2015);
R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

OMEGA shot 77068 extrapolates to a yield of ~5 × 10^{16} and yield amplification of ~2.4× at 1.8 MJ of laser energy





T_i (keV)	3.6
Yield	5.0×10^{13}
ρR (g/cm^2)	0.2
R_{hs} (μm)	22
P (Gbar)*	53
τ (ps)	73

$$Y(77068) \approx 5 \times 10^{13} \longrightarrow 400\times \longrightarrow Y_{\text{no}\,\alpha}(1.8\,\text{MJ}) \approx 2.0 \times 10^{16}$$

$$\chi_{\text{no}\,\alpha}(77068) \approx 0.14 \longrightarrow 4.7\times \longrightarrow \chi_{\text{no}\,\alpha}(1.8\,\text{MJ}) \approx 0.66 \longrightarrow \text{same as high foot}$$

$$\boxed{\frac{Y_\alpha}{Y_{\text{no}\,\alpha}}(1.8\,\text{MJ}) \approx 2.4\times}$$

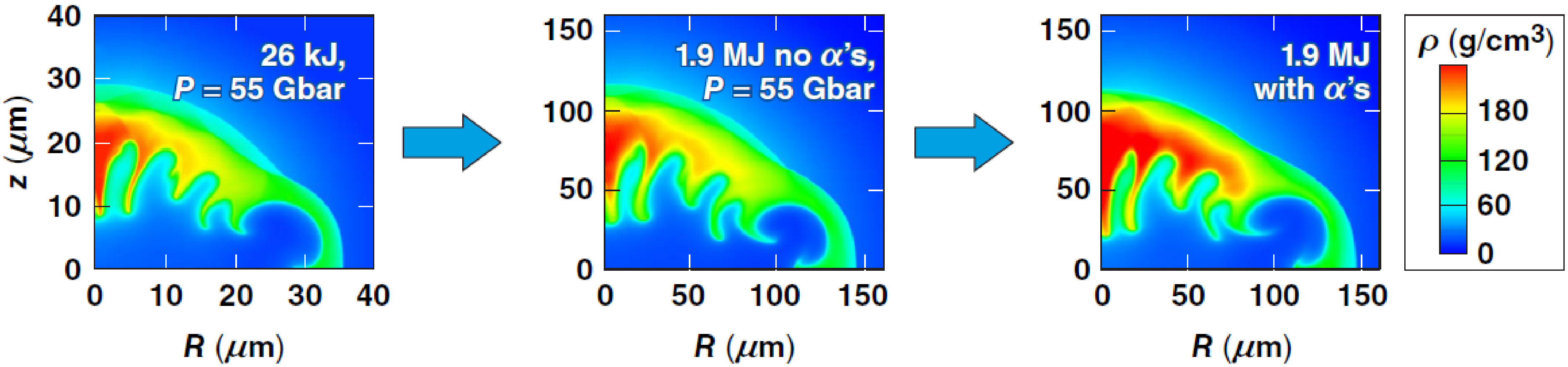
$$\boxed{Y_\alpha(1.8\,\text{MJ}) \approx 5 \times 10^{16} \approx 130\,\text{kJ}}$$

Confirmed by simulations and valid in 3-D

TC12358

A multimode ice perturbation is used to degrade the target performance to reproduce the OMEGA experiment; the same perturbation is applied to the 1.9-MJ target

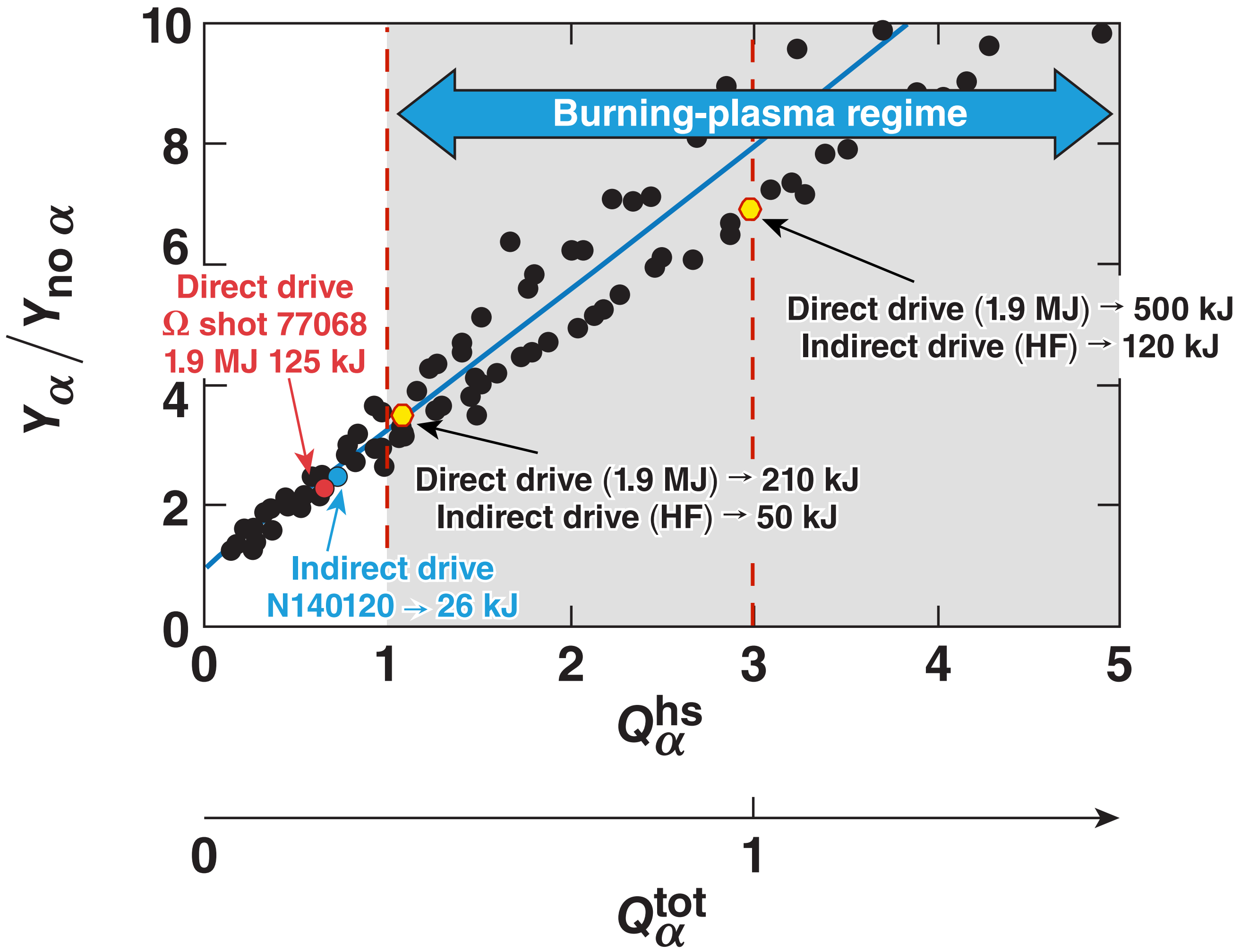
Density at bang time



Yield with α's = 125 kJ
Yield no α's = 63 kJ

$$\boxed{\frac{Y_{\alpha}^{1.9\,\mathrm{MJ}}}{Y_{\mathrm{no}\,\alpha}^{1.9\,\mathrm{MJ}}} \approx 2}$$

Access to the burning-plasma regime requires about 50 kJ of HF targets in indirect drive and about 200 kJ of fusion energy for direct drive



Both direct and indirect drive must double the yield amplification to access the burning-plasma regime.

TC12302c

Summary

The onset of the burning-plasma regime can be identified through experimental observables related to the yield amplification from alpha heating

- The fundamental parameter characterizing burning plasmas is Q_α = alpha heating / PdV work
- Current high-foot* implosions at the National Ignition Facility (NIF) have achieved Q_α^{hs} = 0.5 - 0.6 with a yield amplification caused by alpha heating of about 2.5×
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*O. A. Hurricane *et al.*, Nature 506, 343 (2014);

**R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

Despite the exciting results, the path to ignition is uncertain with current direct- and indirect-drive targets

No-α ignition parameter in terms of in-flight properties

$$\chi_{\text{no }\alpha} \sim E_k^{0.37}\,\text{YOC}^{0.4}\,\frac{V_{\text{imp}}^2}{\alpha_F^{3/5}} \sim E_k^{0.37}\,\text{YOC}^{0.4}\,P_{\text{abl}}^{2/5}\,\text{IFAR}$$

Best shot to date → $\chi_{\text{no }\alpha} \approx 0.65$

E_k = kinetic energy

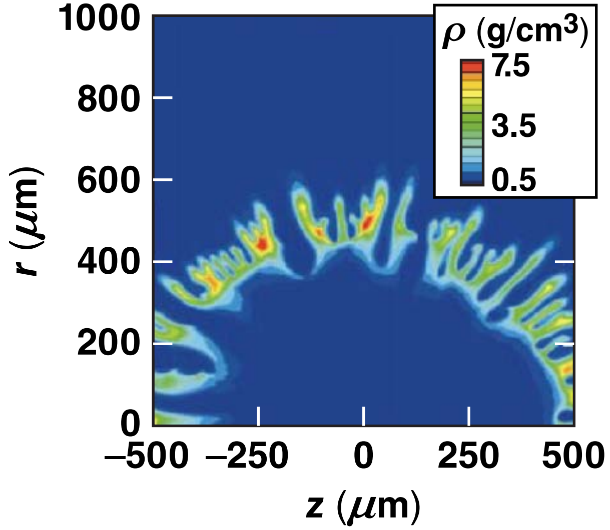
YOC = yield-over-clean = $Y(\text{3-D})/Y(\text{1-D})$

YOC is $\geq$50% in NIF high foot

V_{imp} = implosion velocity

α_F = adiabat (entropy)

Needed for ignition → $\chi_{\text{no }\alpha} \approx 1$



Increasing the IFAR* while preserving the YOC is a challenge.

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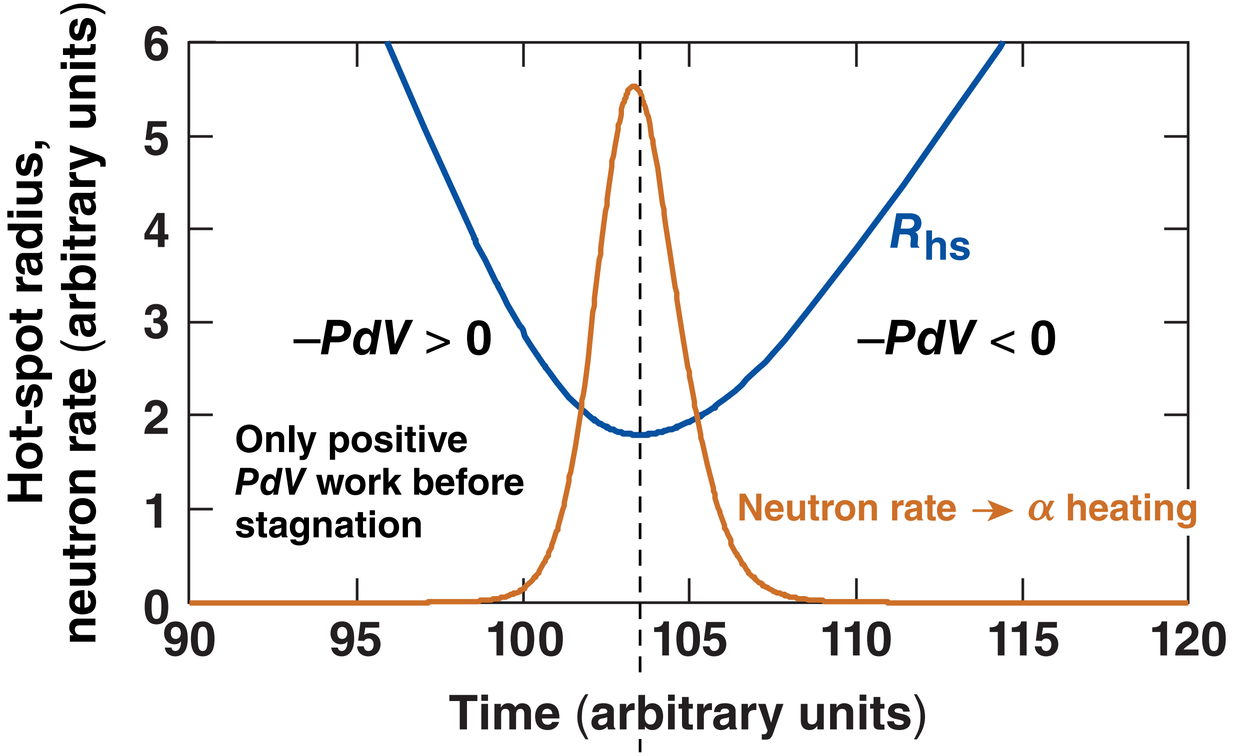
*In-flight aspect ratio

Only half of the α energy can be counted when determining Q_α for ICF



$$\boxed{Q_\alpha^{hs} = \frac{1/2\, E_\alpha}{-PdV_{hs}}}$$

Hot spot Q_α

TC12288

Two burning-plasma regimes are identified:
α heating exceeds *PdV* work to the hot spot
α heating exceeds *PdV* to hot spot + shell

Hot spot Q_α

$$\boxed{Q_\alpha^{hs} = \frac{\frac{1}{2}E_\alpha}{\left|PdV_{hs}\right|}}$$

Total Q_α

$$\boxed{Q_\alpha^{tot} = \frac{\frac{1}{2}E_\alpha}{\left|PdV_{hs}\right| + \left|PdV_{sh}\right|}}$$

- First burning-plasma regime

$$\boxed{Q_\alpha^{hs} \geq 1}$$

- Second burning-plasma regime

$$\boxed{Q_\alpha^{tot} \geq 1}$$

TC12289a