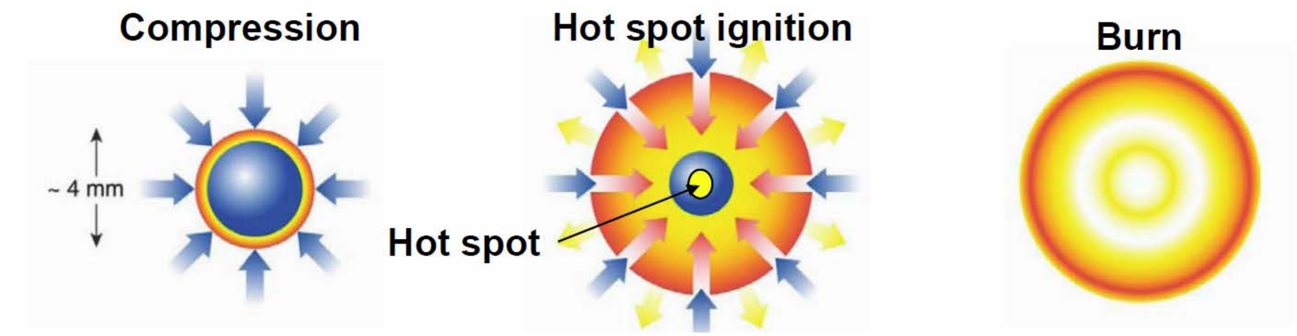
Understanding the critical steps to ignition



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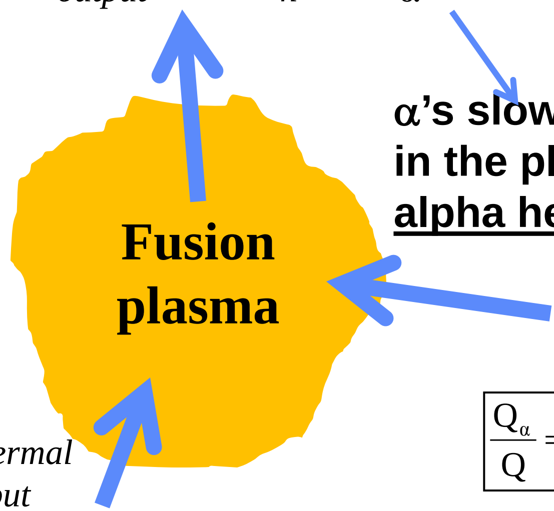
OUTLINE

- → **Definitions: fusion Q, target gain G**
- → **Burning plasmas, ignited plasmas, burn propagation**
- → **The Lawson criterion for ICF**
- → **Relation between the Lawson criterion and the ITFX**
- → **α-heating and burning plasma vs ITFX**

The thermonuclear or fusion Q and the alpha Q

Nuclear Energy (α+n) Output from the Fusion Plasma

$$E_{output}^{nuclear} = E_n + E_\alpha$$



α's slow-down in the plasma, alpha heating

E_α

$E_{input}^{thermal}$

External Thermal Energy Input to the Fusion Plasma

$$\frac{Q_\alpha}{Q} = \frac{3.5\text{MeV}}{17.5\text{MeV}} \Rightarrow Q_\alpha \approx \frac{Q}{5}$$

The fusion Q

$$Q = \frac{E_{output}^{nuclear}}{E_{input}^{thermal}}$$

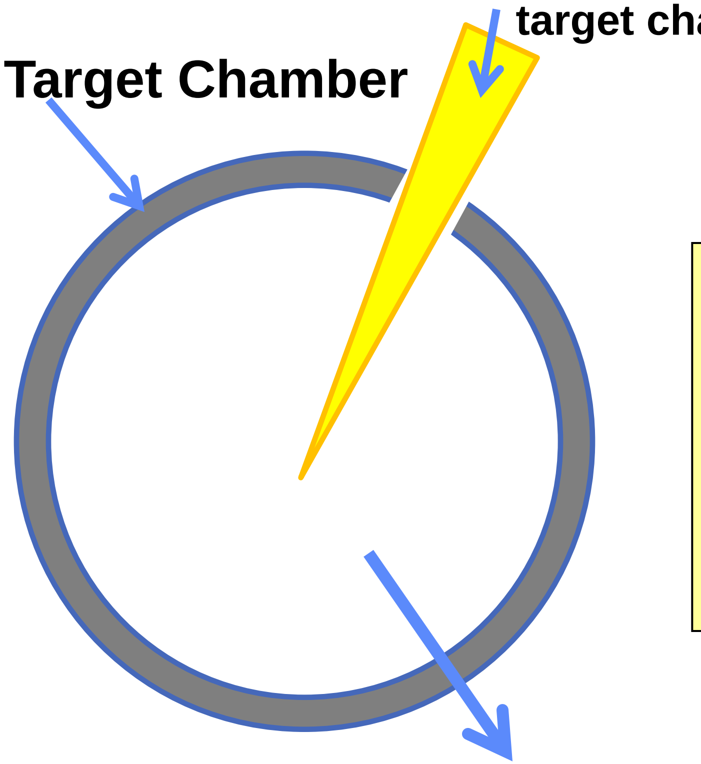
The alpha Q

$$Q_\alpha = \frac{E_\alpha}{E_{input}^{thermal}} = \frac{Q}{5}$$

$Q = 5 \Rightarrow Q_\alpha = 1 \Rightarrow \alpha - \text{heat} = \text{external} - \text{heat}$ ← **Alpha bootstrap heating**

$Q = 10 \Rightarrow Q_\alpha = 2 \Rightarrow \alpha - \text{heat} = 2 \times \text{external} - \text{heat}$ ← **Burning plasma**

The Target Gain "G" is NOT a physics parameter



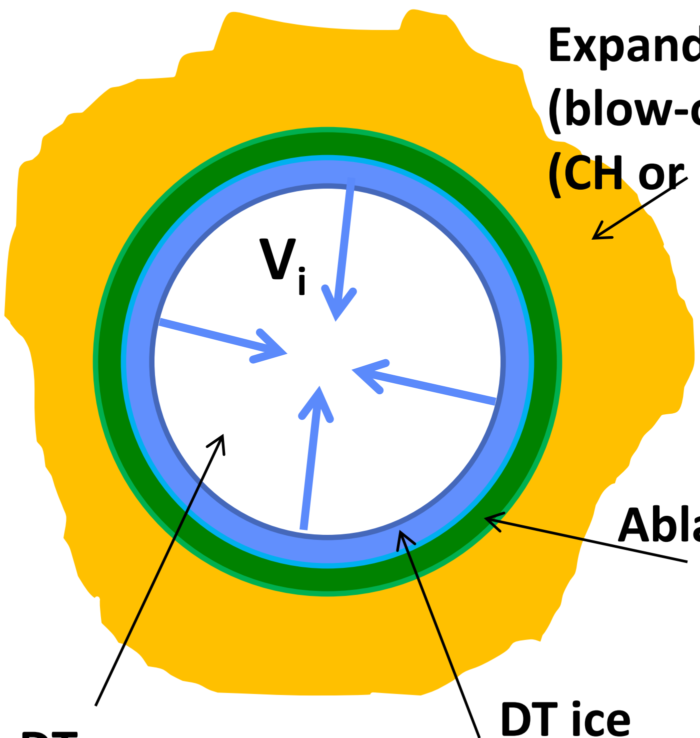
The Target Gain

$$G = \frac{\text{Nuclear Energy Output}}{\text{Driver Energy into Target Chamber}}$$

$$G = \frac{E_{\text{output}}^{\text{nuclear}}}{E_{\text{Driver}}}$$

Driving ICF targets is a very inefficient process

Only a small fraction of the driver energy is converted into useful kinetic energy of the implosion. <u>Most of the driver energy is wasted in heating and accelerating (outward) the blow-off plasma (typically CH or Be plasma)</u>



Examples:

NIF 1MJ Indirect Drive Point Design
Laser energy = 1MJ
Fuel kinetic energy = 10kJ
Total efficiency = 1 %

NIF 1.5MJ Direct Drive Point Design
Laser energy = 1.5MJ
Fuel kinetic energy = 90kJ
Total efficiency = 6%

V_i = implosion velocity

Useful kinetic energy $= \frac{1}{2} M_{unablated}^{shell} V_i^2$

The imploding shell has two functions: (a) heating of the central low-density plasma (hot spot) to ignition temperatures, (b) providing the "inertial" confinement

Useful kinetic energy

$$\frac{1}{2} M^{shell}_{unablated} V_i^2$$

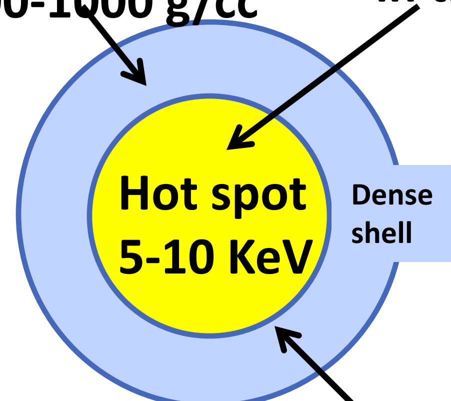
~50% → Compression and heating of the central hot spot (equivalent to the MFE heating input energy <u>coupled</u> to the plasma)

~50% → Compression of the dense shell to provide the "inertial" confinement (similar role to the magnetic field in MFE)

COMPRESSED CORE AT STAGNATION

Dense shell
~ 500-1000 g/cc

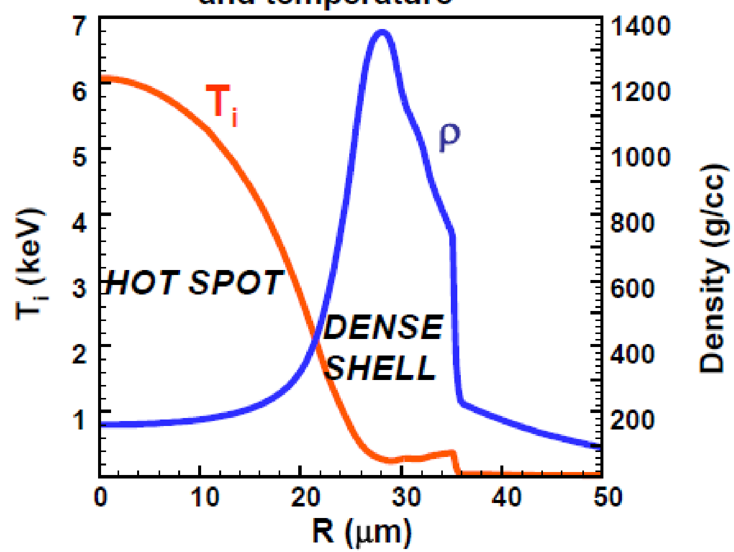
Ignition takes place in the hot spot



Provides the confinement of the hot spot (and more)

Stagnation density and temperature

(NIF-like, 1MJ)



The input energy to the hot spot is small (~several kJ). The thermonuclear instability (ignition) can amplify the input energy by a very large factor

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<u>EXAMPLE: 1MJ YIELD (G=1)</u>

<u>AMPLIFICATION DUE TO IGNITION</u>

Consider (for example):

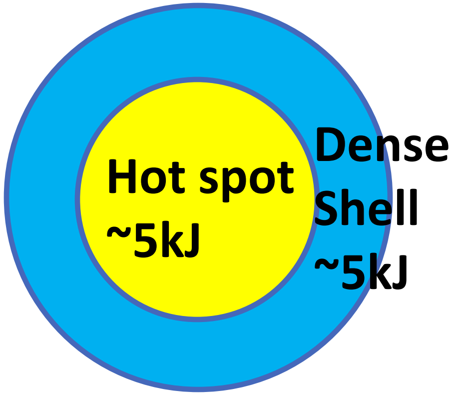
(a) 1MJ fusion (α + n) yield = E_{out}

(b) <u>Fusion-Q →</u> $Q=E_{out}/E_{input\text{-}ext}$

$Q = 1MJ/5kJ = 200$

(c) Alpha-heating level $Q_\alpha = E_\alpha / E_{input\text{-}ext}$

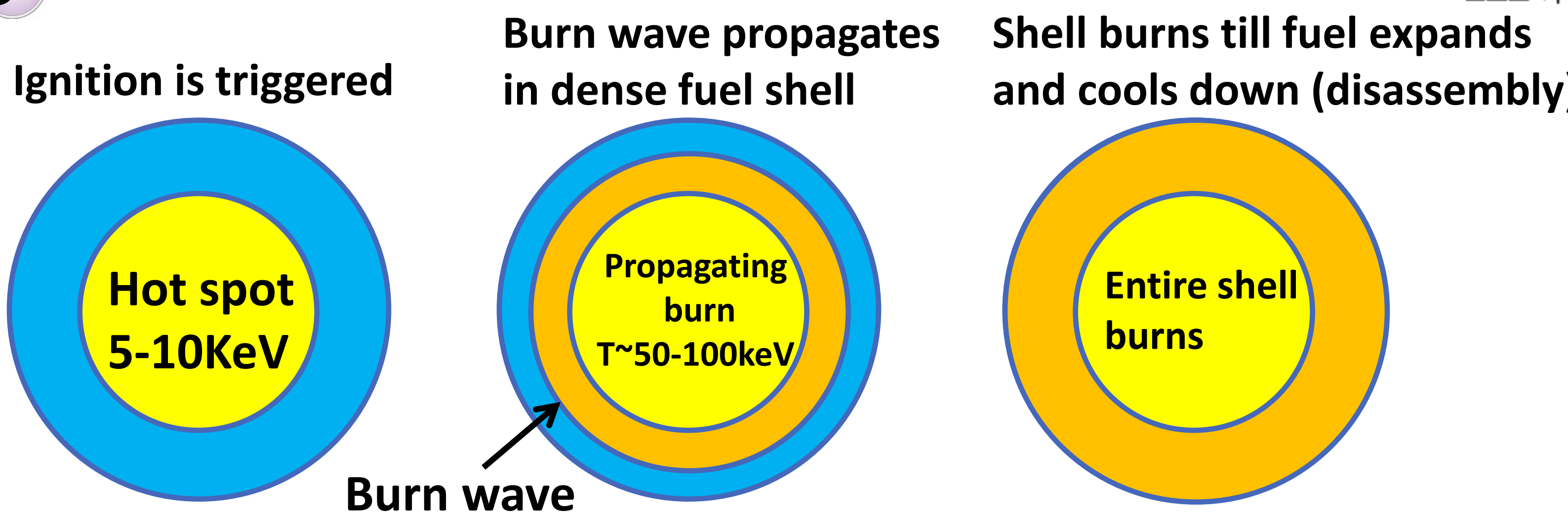
$Q_\alpha = Q/5 = 40$



$Q_\alpha \geq 2$ or $Q \geq 10$ defines a "burning plasma" (typical definition used in MFE)

A Q~100 can be used as a measure of ignition in ICF

In addition to the inertial confinement, the dense shell around the hot spot provides a reservoir of fuel that, if burned, leads to ultra-large amplifications of the hot-spot input energy



Example:

- NIF 1MJ Indirect-Drive point design
- Total kinetic energy = 10kJ
- 5kJ into the hot spot

<u>AMPLIFICATION DUE TO BURN PROPAGATION</u>

Consider a 10 MJ fusion yield (G=10)

Q=10MJ/5kJ=2000

Q_α= Q/5=400

The target Gain can be related to Q_α for a fixed energy (to the target) coupling efficiency

Energy Target Gain:

$$G = \frac{\text{Fusion Energy Output } (\alpha + n)}{\text{Driver Energy \underline{into the Target Chamber}}}$$

Alpha Q = (Fusion Q)/5:

$$Q_\alpha = \frac{\text{Alpha Particle Energy}}{\text{½ Driver Energy \underline{coupled} as kinetic energy}}$$

(½ into the hot spot, ½ into the shell)

Example:
- NIF 1MJ ID point design
- Fuel kinetic energy = 10kJ
- 5kJ into the hot spot

G ~ 0.025 → Q_α ~ 1 → α-heating = input energy to HS (~1e16 neutrons)

G ~ 0.05 → Q_α ~ 2 → Burning plasma (~2e16 neutrons)

G ~ 0.5 → Q_α ~ 20 → Ignition (~2e17 neutrons)

G ~5-20 → Q_α ~ 200-800 → FULL Propagating burn (~2-8e18 neutrons)

The ignition parameter χ from the energy balance determines the plasma performance

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Fusion plasma energy balance

$$W_\alpha + W_{input} = W_{losses} \qquad W_\alpha\left(1+\frac{W_{input}}{W_\alpha}\right) = W_\alpha\left(1+\frac{1}{Q_\alpha}\right) = W_{losses}$$

$$Q_\alpha = \frac{W_\alpha / W_{losses}}{1 - W_\alpha / W_{losses}} = \frac{\chi}{1-\chi}$$

$$\chi \equiv \frac{W_\alpha}{W_{losses}}$$ ← **Ignition parameter**

χ=1 → Q_α = ∞ → Ignition
χ=2/3 → Q_α = 2 → Burning plasmas
χ=1/2 → Q_α = 1 → Alpha bootstrap heating

The Lawson criterion for thermonuclear ignition requires that the alpha-particle heating exceeds all the energy losses

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W_α > W_{losses}

α-particle heating rate > energy loss rate

$$\int_{V_{hot}} dV \varepsilon_\alpha \frac{n^2}{4}\langle \sigma v \rangle > \frac{3}{2}\frac{\langle p \rangle V_{hot}}{\tau_E}$$

ion particle density

Hot plasma volume

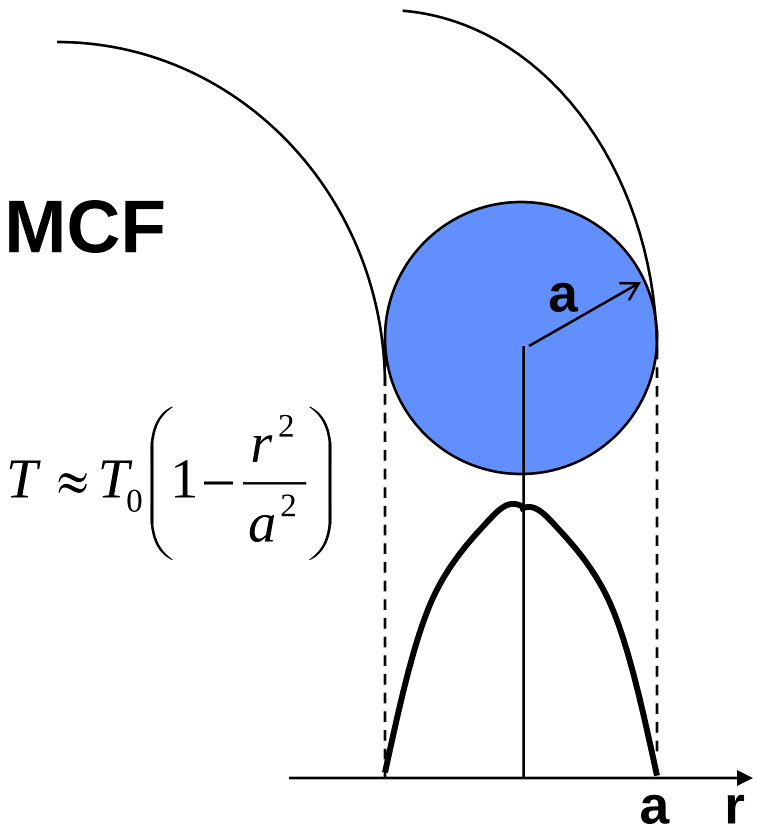
Plasma pressure

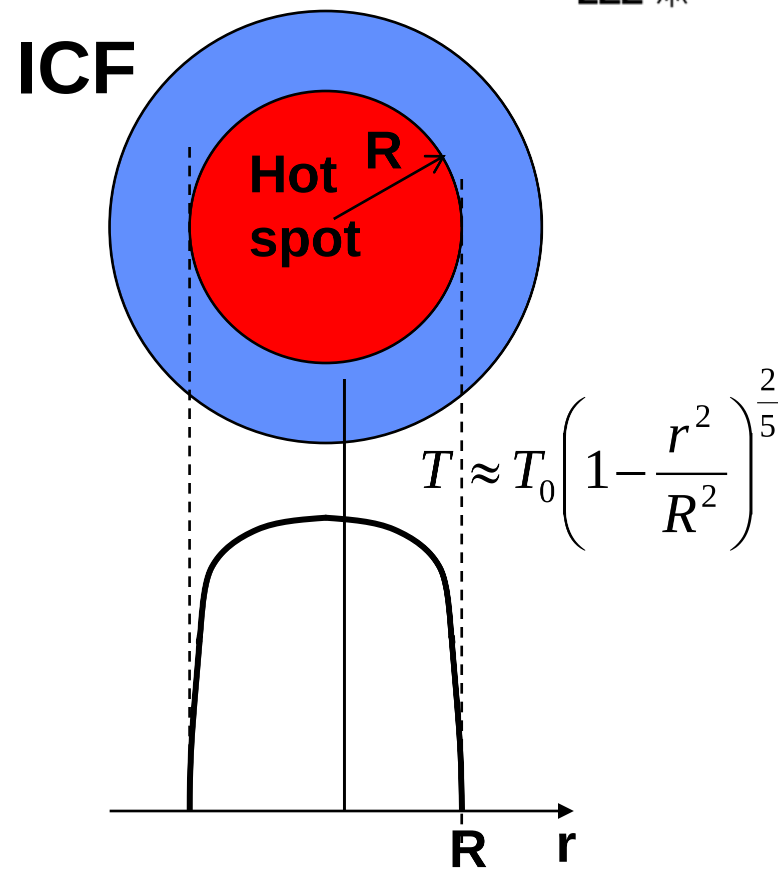
3.5MeV

fusion reactivity

Energy confinement time

A 0-Dimensional model of the thermonuclear instability (ignition) includes the entire plasma column of a tokamak and only the hot spot of an ICF capsule.





Fast radial transport for ITER $\tau_E < \tau_\alpha \rightarrow$ Temperature profile is "consistent or resilient"→0-D model is ok and includes the entire plasma.

Cold dense shell does not contribute to ignition.
Only hot spot ignites.
Shell supplies fuel

Profiles effects need to be included in the calculation of the Lawson criterion

$$\langle p \rangle \tau_E > \frac{24}{\varepsilon_\alpha S\left(\langle T \rangle\right)}$$

MCF

$n \approx const$

$$T \approx T_0 \left(1 - \frac{r^2}{R^2}\right)$$

ICF

$p \approx const$

$$T \approx T_0 \left(1 - \frac{r^2}{R^2}\right)^{2/5}$$

$$S_{MCF} = \frac{\langle\langle \sigma v \rangle\rangle}{\langle T \rangle^2}$$

$$S_{ICF} = \left\langle \frac{\langle \sigma v \rangle}{T^2} \right\rangle$$

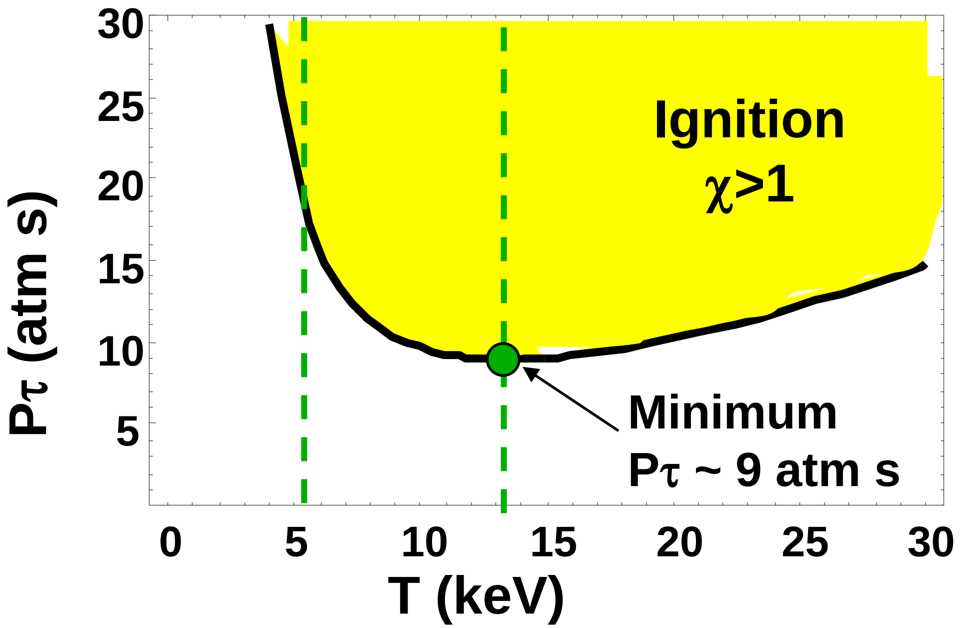
The Lawson parameter Pτ required for ignition depends on the ion temperature

$$\langle p \rangle \tau_E > \frac{24}{\varepsilon_\alpha S(\langle T \rangle)}$$

Overall ignition parameter:

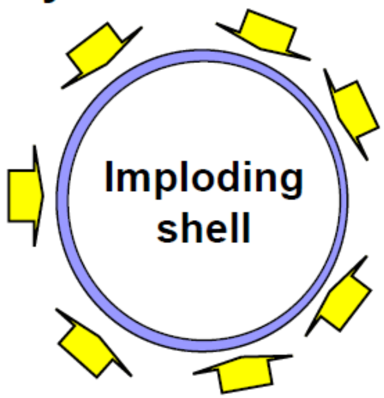
$$\chi \equiv \frac{\langle p \rangle \tau_E}{\left[\langle p \rangle \tau_E\right]_{ign}}$$

$$\left[\langle p \rangle \tau_E\right]_{ign} \equiv \frac{24}{\varepsilon_\alpha S(\langle T \rangle)}$$

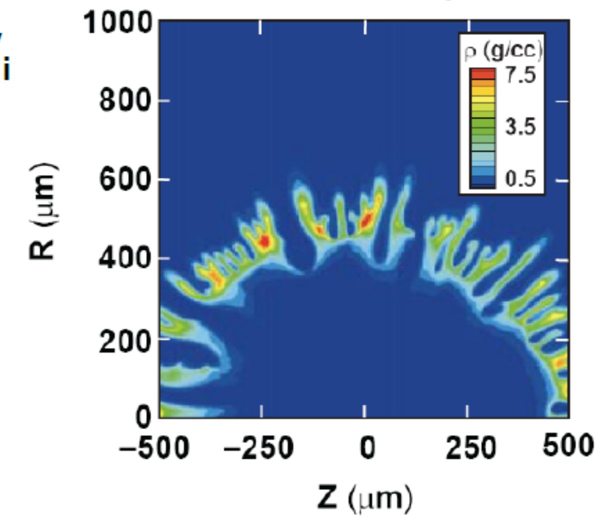


ICF implosions cannot achieve ~10keV temperatures through compression alone

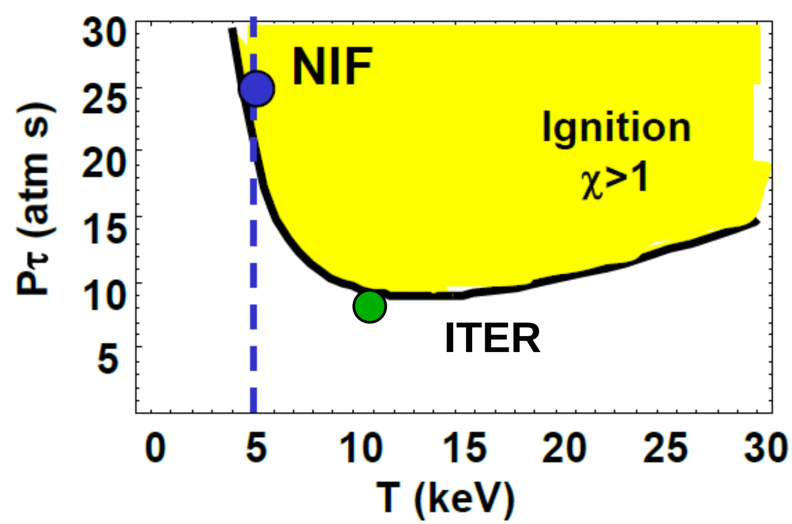
- High T requires high implosion velocity V_i
- High V_i requires thin shells
- Thin shells break up in flight due to hydrodynamic instabilities



$$T \sim V_i$$



ICF needs to operate at ~ 5keV requiring V~400km/s and P~25 atm s.



The expansion losses represent the internal energy lost by the hot spot and transferred to the surrounding dense shell as kinetic energy

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$$1/\tau_{exp} \sim \sqrt{\ddot{R}_{hs}/R_{hs}}$$ **Expansion**

$$M_s \ddot{R}_{hs} = 4\pi P_{hs} R_{hs}^2$$ **Shell Newton's law**

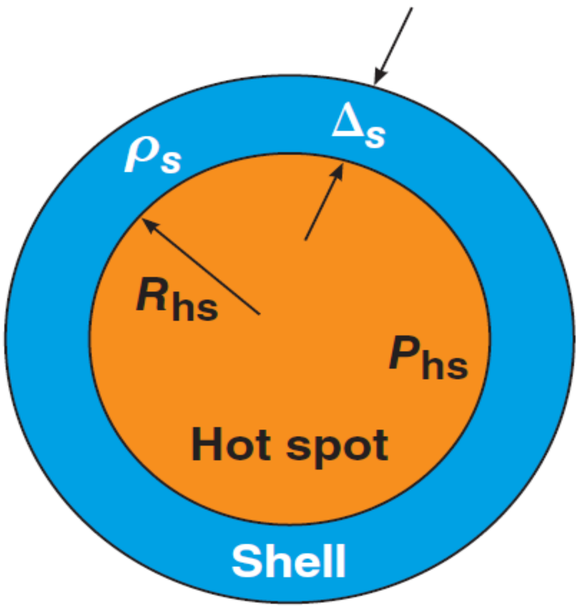
$$M_s \sim \rho_s \Delta_s R_s^2$$

Δ_s = shell thickness

Shell areal density

$$\frac{1}{\tau_{exp}} \sim \sqrt{\frac{P_{hs} R_{hs}}{M_s}}$$

Shell mass



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The ignition condition depends on shell areal density, implosion velocity, and hot-spot ion temperature

Hot-spot pressure and temperature

$$\chi \sim \sqrt{\frac{P_{hs}}{R_{hs}} M_s \frac{\langle \sigma v \rangle}{T_i^2}} > \text{const}$$

Hot-spot radius — Shell mass

$\langle \sigma v \rangle \sim C_\alpha T^3$

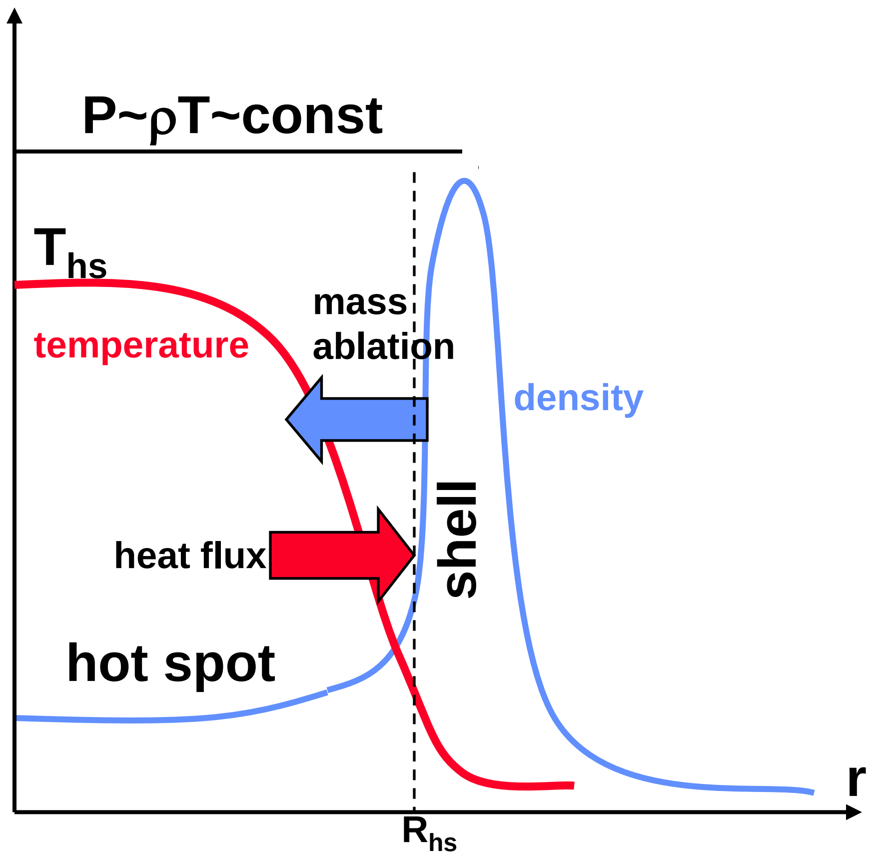
for $4 < T_i < 8$ keV

- $P_{hs} \sim \left(P_{hs} R_s^3\right) / R_s^3 \sim \left(M_s V^2\right) / R_s^3$
- $M_s \sim \rho_s \Delta_s R_s^2$
- $R_s \sim R_{hs}$

$$\chi \sim \left(\rho_s \Delta_s\right) V T_i > \frac{\text{const}}{C_\alpha}$$

Shell areal density — Implosion velocity

The heat flux leaving the hot spot is deposited onto the shell surface causing mass ablation from the shell into the hot spot. The hot spot mass increases in time.



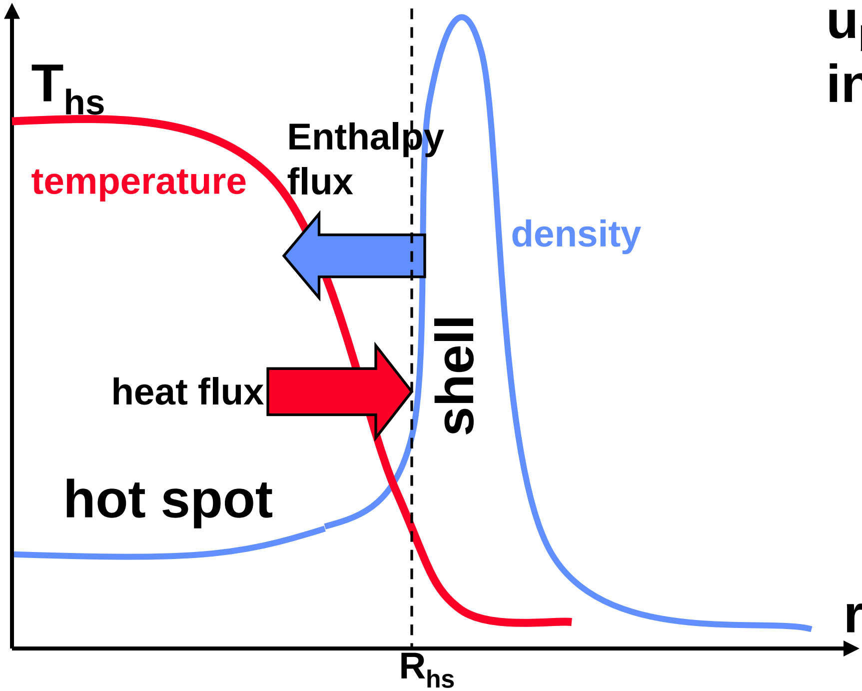
$$q_{heat} = -\kappa(T)\nabla T$$

$$\kappa(T) \approx \kappa_0 T^{5/2}$$

The heat leaving the hot spot cannot penetrate the shell because the shell is cold and its thermal conductivity is low,

$$\kappa_{shell} << \kappa_{hot\ spot}$$

The heat is deposited on the shell inner surface causing mass ablation off the shell



u_b = blow-off velocity into hot spot

$$\frac{5}{2} p u_b = \left[-\kappa_0 T^{5/2} \frac{dT}{dr}\right]_{r=R_{hs}^-}$$

Enthalpy flux

Heat flux

find

- **Hot spot temperature profile →** $T_{hs} = T_0 \left(1 - \frac{r^2}{R_{hs}^2}\right)^{2/5}$
- **Use ideal gas EOS:** $p u_b = 2 \rho_{R_{hs}} T_{R_{hs}} u_b / m_i = 2 \dot{m}_A T_{R_{hs}} / m_i$
- **Ablation rate into hot spot:** $\dot{m}_A = \rho_{R_{hs}} u_b$

$$\dot{m}_A = 0.2 \frac{m_i \kappa_0 T_0^{5/2}}{R_{hs}}$$

Hot spot density

Hot spot volume ~ R_{hs}^3

Use EOS $\rho = m_i p / 2T$

$$M_{hs} = \rho_{hs} V_{hs} = \frac{m_i}{2} \frac{p V_{hs}}{T_{hs}}$$

Hot spot mass evolution →

$$\frac{dM_{hs}}{dt} = 4\pi R_{hs}^2 \dot{m}_A \Rightarrow m_i \frac{p V_{hs}}{tT} \sim R_{hs}^2 \frac{m_i \kappa_0 T^{5/2}}{R_{hs}}$$

Hot spot compression time →

$$t \sim \frac{R_{hs}}{V_I}$$

$$p V_{hs} \sim M_{shell} V_I^2$$

← Energy Conservation (hot spot internal energy comes from shell kinetic energy)

Implosion velocity

$$M_{shell} \sim \rho_s \Delta_s R_{hs}^2$$

Hot spot → temperature

$$T \sim \left(\frac{M_{shell} V_I^3}{\kappa_0 R_{hs}^2} \right)^{2/7} \sim \frac{1}{\kappa_0^{2/7}} \left[(\rho \Delta)_{shell}^{stag} \right]^{2/7} V_I^{6/7}$$

Shell areal density

Relation between implosion velocity, hot temperature and shell areal density leads to ignition parameter

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$$V_I \sim \frac{T^{7/6}}{(\rho\Delta)^{1/3}}$$

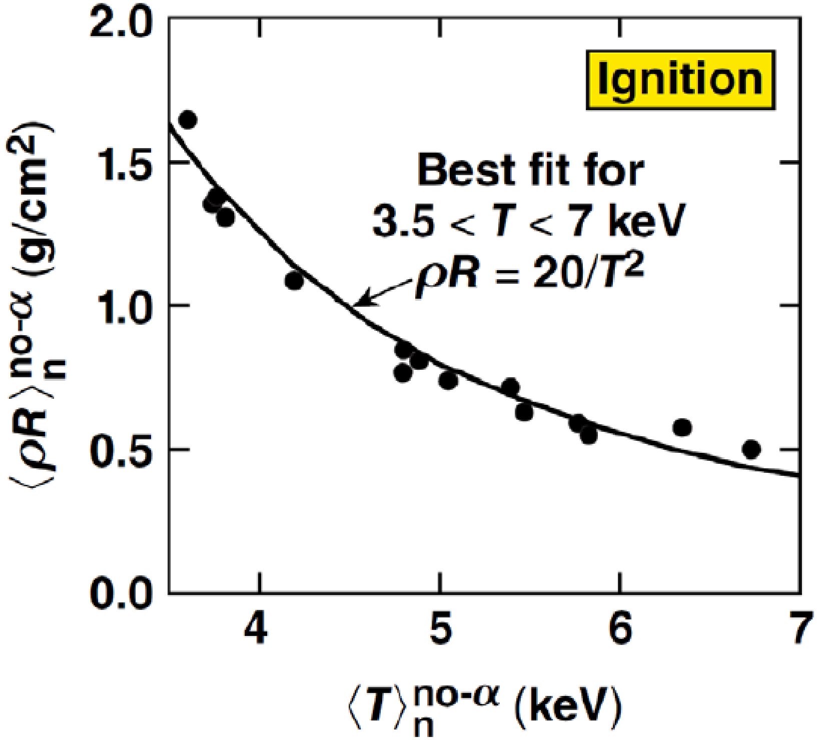
Simple model, thin shell, analytic

$$V_I\,(km/s) \approx 100\,\frac{T^{0.81}}{(\rho\Delta)^{0.17}}$$

Better model, thick shell, numerical

$$\chi \sim \left[(\rho\Delta)\,T_i^{2.1}\,\cancel{\alpha_{if}^{0.03}}\right]^{0.83} > const/C_\alpha$$

The analytic model agrees reasonably well with the simulations; the latter can be accurately fit by a simple power law $\rho R \times T^2 > 20$ for $3.5 < T < 7$ keV



Ignition condition

1-D ignition parameter

$$\chi_{1\text{-D}} \equiv \left\langle \rho R^{\text{no-}\alpha}_{\text{g/cm}^2} \right\rangle_n^{0.8} \left(\frac{\left\langle T^{\text{no-}\alpha}_{\text{keV}} \right\rangle_n}{4.7} \right)^{1.6} > 1$$

$3.5 < T^{\text{no-}\alpha}_{\text{keV}} < 7$

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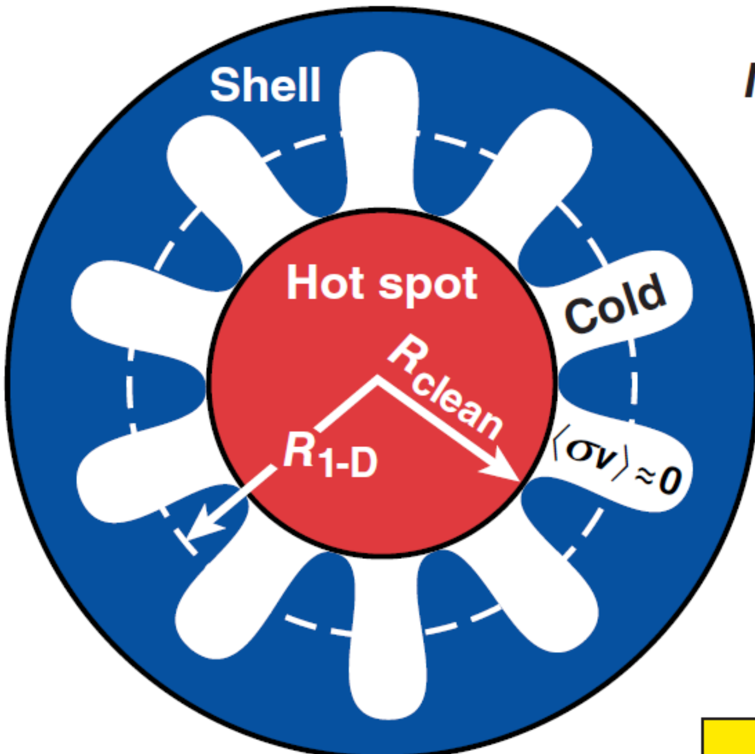
In 3-D the fusion yield is reduced by the Rayleigh–Taylor instability that cools down parts of the hot spot



$$V_{\text{3-D}}^{\text{clean}} \sim R_{\text{clean}}^{3} < V_{\text{1-D}} \sim R_{\text{1-D}}^{3}$$

$$N_{\text{neutron}}^{\text{3-D}} \sim n_i^2 \langle \sigma v \rangle V_{\text{3-D}}^{\text{clean}} \tau_{\text{burn}} \sim N_{\text{neutron}}^{\text{1-D}} \frac{V_{\text{3-D}}^{\text{clean}}}{V_{\text{1-D}}}$$

- The yield-over-clean YOC = 3-D fusion yield; 1-D yield is approximately equal to the ratio clean volume/1-D volume

Can be measured

$$\text{YOC} \equiv \frac{N_{\text{neutron}}^{\text{3-D}}}{N_{\text{neutron}}^{\text{1-D}}} \approx \frac{V_{\text{3-D}}^{\text{clean}}}{V_{\text{1-D}}}$$

YOC without α-deposition $\text{YOC}^{\text{no}-\alpha}$

TC8551

The YOC is used to extend the measurable Lawson criterion to three dimensions

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Back to the 1-D Lawson criterion (simple analytic model)

$$(\rho R)_{\text{st}}^{\text{no-}\alpha\;0.8}\left(T_{\text{st}}^{\text{no-}\alpha}\right)^{1.7} > \text{const}/C_{\alpha}$$

$$C_{\alpha} \sim \int_{V}\langle\sigma v\rangle dV$$

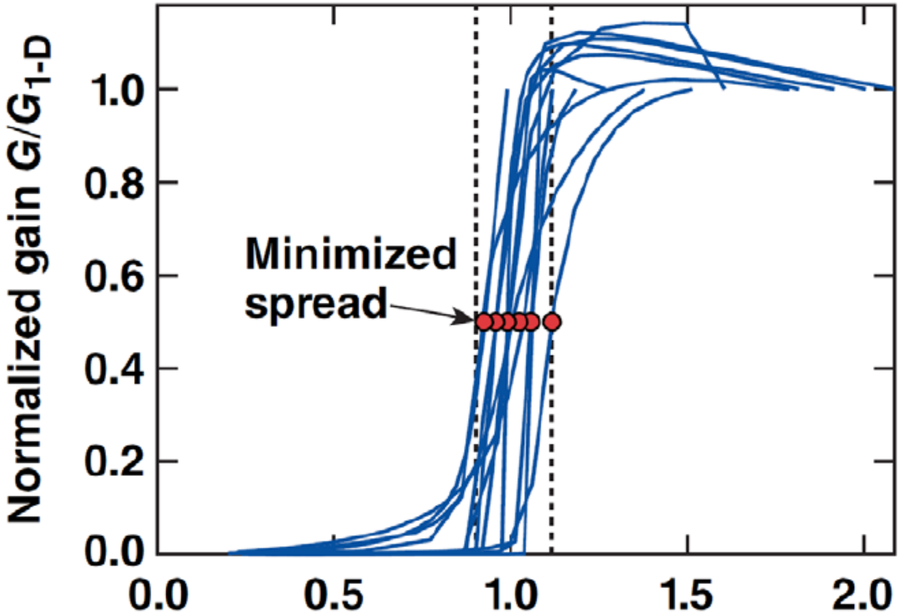
$$C_{\alpha}^{\text{3-D}} \sim \int_{V_{\text{3-D}}}\langle\sigma v\rangle dV \approx C_{\alpha}^{\text{1-D}}\frac{V_{\text{3-D}}^{\text{clean}}}{V_{\text{1-D}}} \approx C_{\alpha}^{\text{1-D}} \cdot \text{YOC}^{\text{no-}\alpha}$$

3-D measurable Lawson criterion

$$(\rho R)_{\text{st}}^{\text{no-}\alpha\;0.8}\left(T_{\text{st}}^{\text{no-}\alpha}\right)^{1.7}\left(\text{YOC}^{\text{no-}\alpha}\right) > \text{const}$$

Power 0.8 in better analytic model

Results from a 2-D + pseudo 2-D simulation database are in reasonable agreement with the ignition model



$$\chi_{sim}^{fit} = (\rho R_{g/cm^2}^{no-\alpha})^{0.8} \left(\frac{T_{keV}^{no-\alpha}}{4.7} \right)^{1.6} YOC_{no-\alpha}^{0.4}$$

3-D Measurable Lawson Criterion (fit from simulations)

The product Pτ can be derived by using a power-law approximation for the fusion reactivity

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$$\chi = \frac{\langle \sigma v \rangle \varepsilon_\alpha P\tau}{24T^2} = \frac{P\tau}{[P\tau]_{ign}^{\min}}$$

Overall ignition parameter

$$\chi \approx (\rho R_{g/cm^2}^{no-\alpha})^{0.8} \left(\frac{T_{keV}^{no-\alpha}}{4.7} \right)^{1.6} YOC_{no-\alpha}^{0.4}$$

$$[p\tau]_{ign}^{\min} \sim \frac{T^2}{\langle \sigma v \rangle} \sim \frac{1}{T}$$

$$P\tau(atm \bullet s) \approx 8(\rho R_{g/cm^2} T_{keV})^{0.8} YOC^{0.4}$$

The product Pτ for NIF and OMEGA

$$P\tau(atm \bullet s) \approx 8(\rho R_{g/cm^2} T_{keV})^{0.8} YOC^{0.4}$$

- **NIF (current): $\langle\rho R\rangle$=1g/cm^2, $\langle T\rangle$=3.5keV, YOC=0.05-0.1**

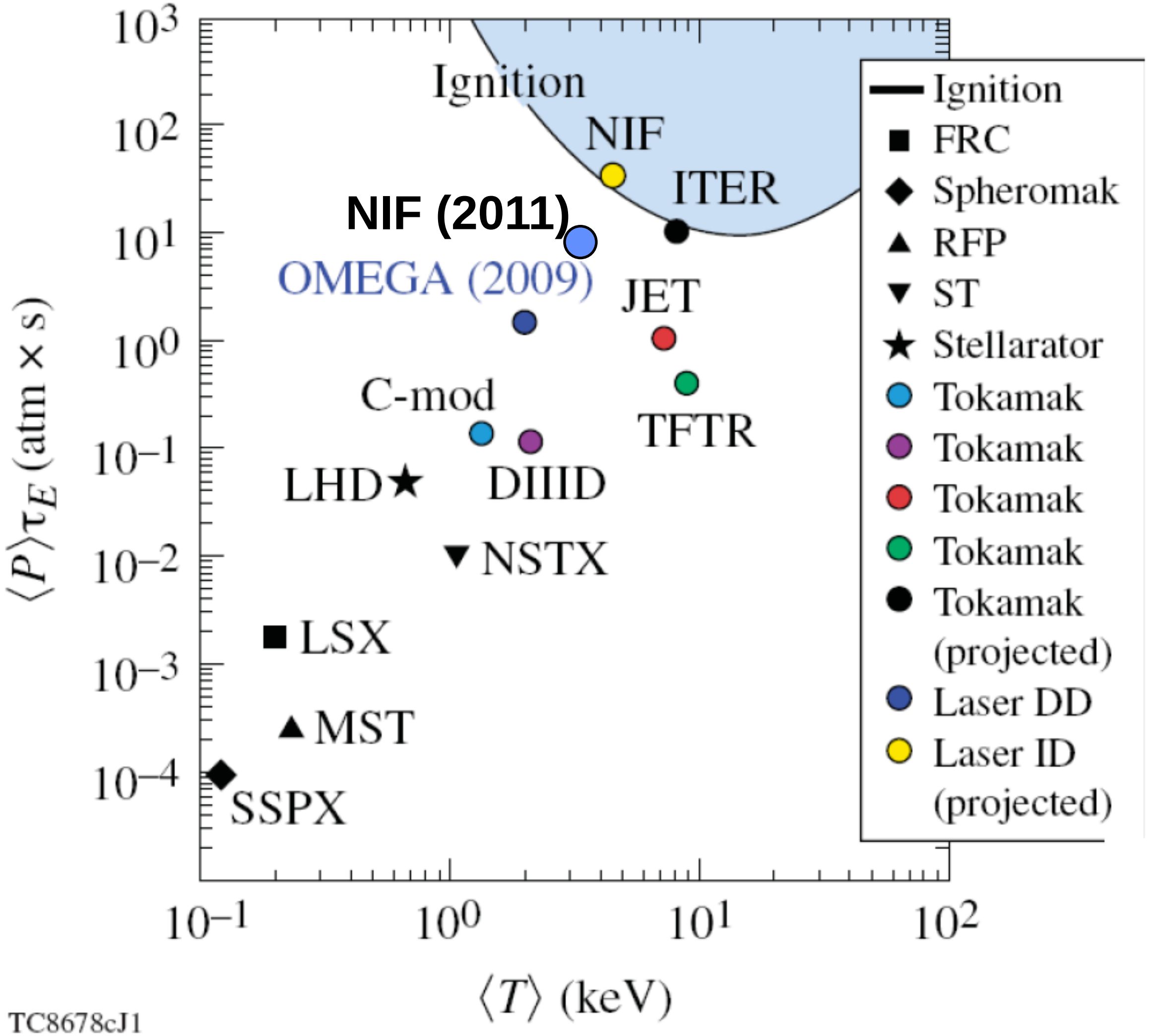
$$P\tau \approx 7 - 10 atm \bullet s$$

- **NIF (check): use directly inferred values; P≈80Gbar, τ_{burn} ≈100ps →P τ_{burn} ~8 atm s**

- **OMEGA (current): ρR=0.24g/cm^2, T=2keV, YOC=0.1**

$$P\tau \approx 1.5 atm \bullet s$$

The Lawson plot shows the performance of fusion devices with respect to thermonuclear ignition



The Lawson criterion, the ITFX, and the fusion and alpha Q

The one-dimensional no-burn neutron yield can be determined from hot spot and shell scaling relations

- **The Yield-Over-Clean requires the 1D Yield without burn (no-α)**

$$Y(1D)^{no-\alpha} \approx \int_0^\infty dt \int_{V_{hs}} n^2 \langle \sigma v \rangle dV \sim p^2 R_{hs}^3 \frac{\langle \sigma v \rangle}{T^2} \tau_b$$

no-α T≤5keV

$$Y(1D)^{no-\alpha} \sim \left(pR_{hs}^3\right)\left(\rho_{hs} T_{hs}\right) T_{hs}^{1.7} \frac{R_{hs}}{V_I} \sim M_{sh} \left(\rho_{hs} R_{hs} V_I\right) T_{hs}^{2.7}$$

- **Need to find** $\left(\rho_{hs} R_{hs} V_I\right)$

Use hot spot mass scaling to find $\left(\rho_{hs} R_{hs} V_I\right)$

$$M_{hs} \sim \rho_{hs} R_{hs}^3 \sim \frac{p R_{hs}^3}{T_{hs}} \sim \frac{M_{sh} V_I^2}{T_{hs}} \sim \frac{(\rho\Delta)_{sh} R_{sh}^2 V_I^2}{T_{hs}}$$

Hot spot areal density depends on shell areal density

$$\rho_{hs} R_{hs} \sim (\rho\Delta)_{sh} \frac{V_I^2}{T_{hs}}$$

Use previously derived scaling of hot spot temp and velocity

$$V_I \sim \frac{T_{hs}^{0.8}}{\left(\rho\Delta\right)_{sh}^{0.17}}$$

Find: $\rho_{hs} R_{hs} V_I \sim (\rho\Delta)_{sh}^{0.5} T_{hs}^{1.4}$

The 1D compression yield depends on shell areal density, hot spot temperature and fuel mass

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Scaling from simple model

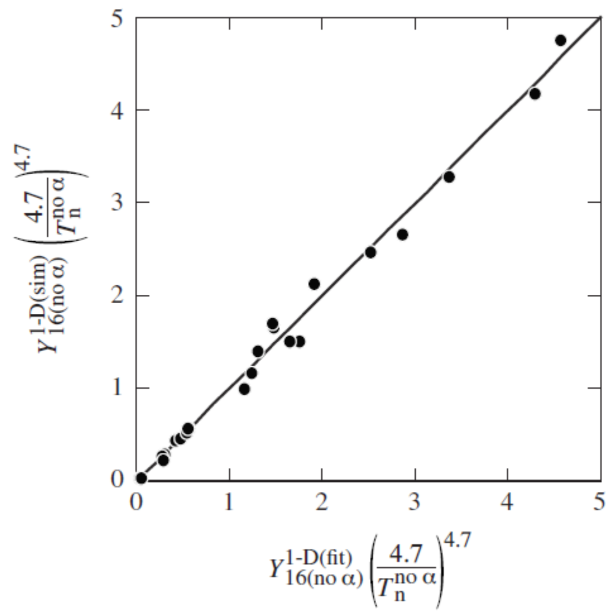
$$Y(1D)^{no-\alpha} \sim (\rho\Delta)_{sh}^{0.5} T_{hs}^{4.1} M_{sh}$$

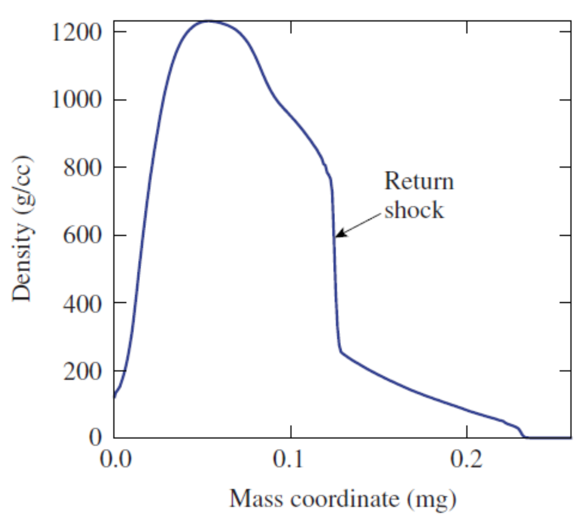
Fit of simulations

$$Y(1D)_{16}^{no-\alpha} \sim (\rho\Delta)_{sh(g/cm^2)}^{0.56} \left(\frac{T_{hs}^{keV}}{4.7}\right)^{4.7} \frac{M_{sh}(mg)}{0.12}$$

Stagnating shell mass is about ½ of fuel mass

$$M_{sh} \approx \frac{1}{2} M_{DT}$$





The Lawson ignition parameter for ICF can be written in terms of neutron yield, areal density and fuel mass

$$\chi \approx (\rho R^{no-\alpha}_{g/cm^2})^{0.8} \left(\frac{T^{no-\alpha}_{keV}}{4.7} \right)^{1.6} \left(\frac{Y_n}{Y_{1D}} \right)^{0.4}_{no-\alpha}$$

$$Y(1D)^{no-\alpha} \sim (\rho \Delta)^{0.56} (T_{hs})^{4.7} M_{sh}$$

$$\chi \sim \rho R^{0.7} \left(\frac{Y_n^{no-\alpha}}{M_{sh}} \right)^{0.4} \chi_{1D}^{-0.17} \sim \rho R^{0.7} \left(\frac{Y_n^{no-\alpha}}{M_{sh}} \right)^{0.4}$$

Close to unity (neglect)

The LLNL ITFX is a approximately a power of the Lawson ignition parameter

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Lawson criterion = $\chi \equiv \frac{P\tau}{P\tau(T)_{ign}} > 1$

Alternate forms of χ: $\chi \approx \rho R_n^{0.8} \times \left(\frac{0.1 Y_{DT}^{no-\alpha} 10^{-16}}{M_{stagnation}^{mg}} \right)^{0.45}$ Best fit of simulations

LLNL ITFX for fixed fuel mass (Spears et al): $ITFX \sim dsf\,^2 Y_{DT}^{no-\alpha}$

dsf~ρR

$$ITFX \approx \chi^2$$

Current NIF: $ITFX = 0.09 \Rightarrow \chi_{from-ITFX} \sim 0.3, \quad \chi_{direct} \sim 0.2$

Current OMEGA: $ITFX = 9 \bullet 10^{-4} \Leftarrow \chi \approx 0.03$

JET (1999): $\chi \approx 0.13$

A four fold increase in fusion yield is required in the NIC experiments to access the alpha bootstrap heating regime

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$$\chi = \frac{Q}{Q+5} \Rightarrow Q = \frac{5\chi}{1-\chi}$$

$$\chi = \frac{Q_\alpha}{Q_\alpha + 1} \Rightarrow Q_\alpha = \frac{\chi}{1-\chi}$$

Current NIC experiments: $\chi \approx 0.2 \Rightarrow Q \approx 1.3 \Rightarrow Q_\alpha \approx 0.25$

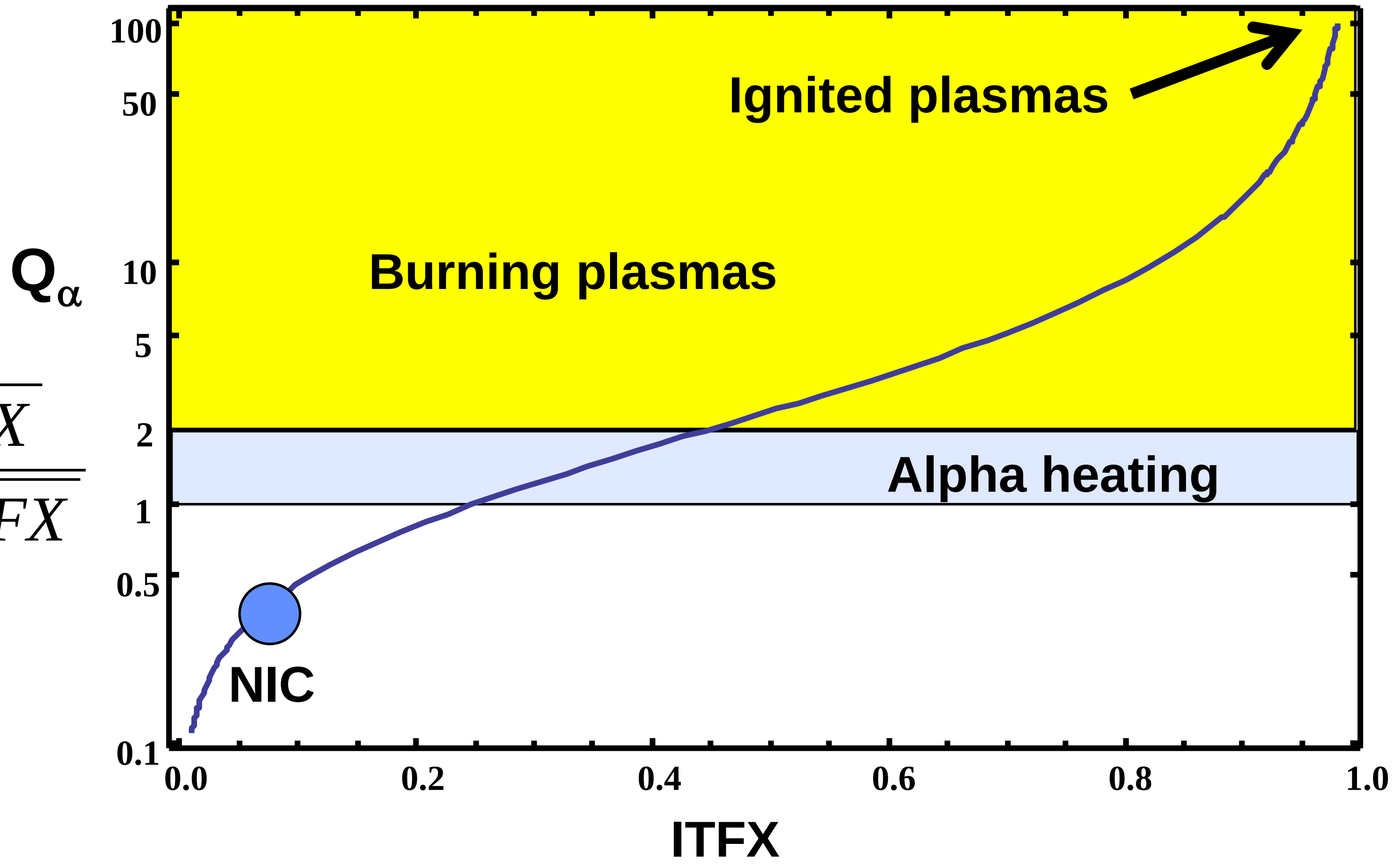
- **NIF hot spot; ~80Gbar, ~35μm-radius →(3/2)PV~2.4kJ**
- **NIF neutron yield ~ 1e15 ~2.8kJ**

NIC → 2.4kJ in hot spot → 2.8kJ fusion yield →Q~1.2→ Q_α~0.25

Alpha heating	$Q \approx 5 \Rightarrow Q_\alpha \approx 1 \Rightarrow \chi \approx 0.5$
Burning plasma	$Q \approx 10 \Rightarrow Q_\alpha \approx 2 \Rightarrow \chi \approx 0.7$

An ITFX above ~0.3 is required for alpha bootstrap heating and above ~0.5 for accessing the burning state

$$Q_\alpha = \frac{\sqrt{ITFX}}{1-\sqrt{ITFX}}$$



The ITFX is approximately a power law of the Lawson's ignition parameter and is a good measure of the implosion performance

- The Lawson ignition parameter $\chi \equiv P\tau/(P\tau)_{ign}$ is derived for ICF capsules

- The ITFX is approximately equal to χ^2 (±30%)

- α-heating requires ITFX~0.3 → χ~0.5 → Q_α~1

- Burning plasmas require ITFX~0.5 → χ~0.7 → Q_α~2

- Current NIC experiments: ITFX~0.09 → χ~0.2-0.3 → Q_α~0.25