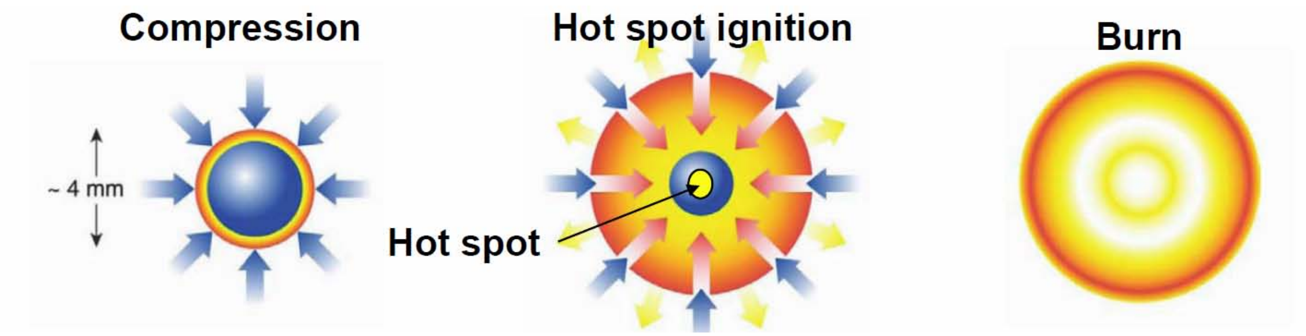
Tutorial on the Physics of Inertial Confinement Fusion

for energy applications



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OUTLINE

- **The PHYSICS of ignition and gain**
  - → Definitions: Q, G, Q_E
  - → Burning plasmas, ignited plasmas, burn propagation
  - → Relations between Target Gains and Q

- **The implications of ignition to fusion ENERGY production**
  - → Does the NIF address all the plasma-target PHYSICS issues for IFE?
  - → The ENGINEERING Q ("Q_E") and its relation to the Target Gains
  - → The need for High Target Gains
  - → Ways to increase the Target Gains

$Q_{Physics}$, Target Gain, $Q_{Engineering}$

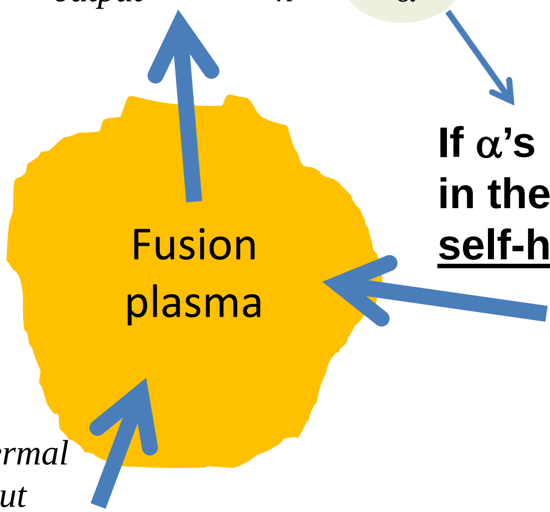
Q, G, Q_E

The Physics or Thermonuclear Q

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

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

If α's slow-down in the plasma, they <u>self-heat</u> the plasma



E_α

$E_{input}^{thermal}$

External Thermal Energy Input to the Fusion Plasma

The Physics or Thermonuclear Q

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

The Physics Q determines the level of self-heating of the fusion plasma.

A better physics parameter is Q_α

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

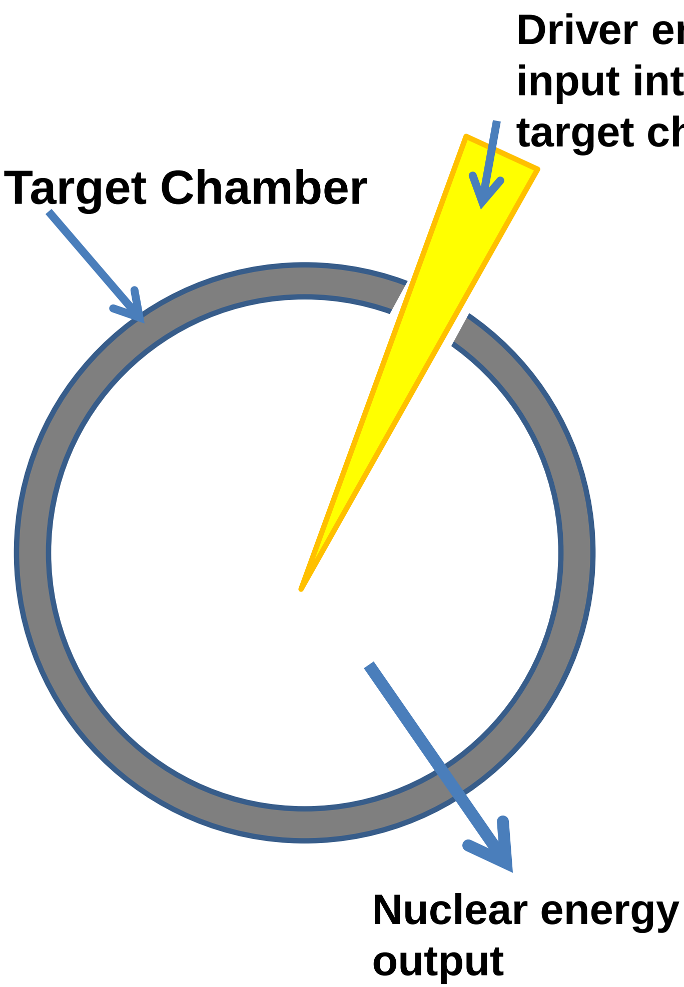
$$\frac{Q_\alpha}{Q} = \frac{3.5\text{MeV}}{17.5\text{MeV}} \Rightarrow Q_\alpha \approx \frac{Q}{5}$$

$$Q = 5 \Rightarrow Q_\alpha = 1 \Rightarrow \alpha - \text{heat} = \text{external} - \text{heat}$$

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

Q=10 → α-dominated plasma → common definition of "burning plasmas"

The Target Gain "G"



The Target Gain

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

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

For example:
NIF is currently a E_D=1-1.3MJ driver in the UV
Expected to reach E_D=1.8MJ

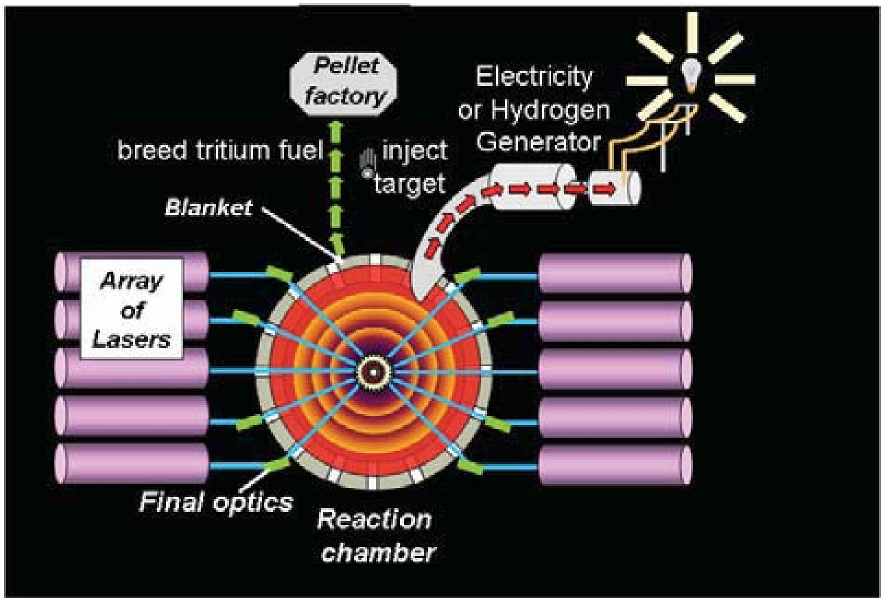
The Engineering Q or "Q_E"

$$Q_E = \frac{E^{\mathrm{NET-electrical}}_{\mathrm{output}}}{E^{\mathrm{electrical}}_{\mathrm{input}}} = \frac{E^{\mathrm{electrical}}_{\mathrm{output}} - E^{\mathrm{electrical}}_{\mathrm{input}}}{E^{\mathrm{electrical}}_{\mathrm{input}}}$$

or

$$\boxed{Q_E = \frac{E^{\mathrm{electrical}}_{\mathrm{output}}}{E^{\mathrm{electrical}}_{\mathrm{input}}}}$$

We will use this definition.

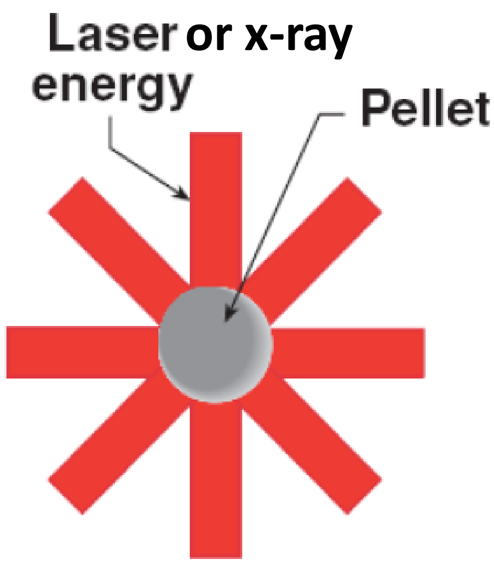


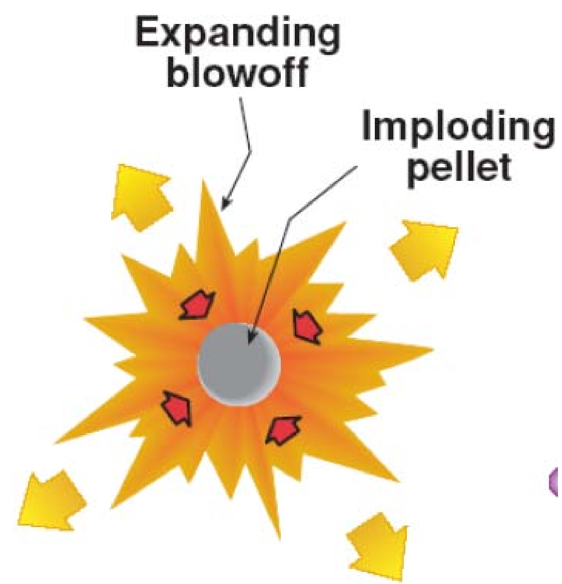
$\boxed{Q_E = 1 \Rightarrow \text{Electrical Power Breakeven}}$

$\boxed{Q_E = 5 \Rightarrow 20\% \text{ Recirculating Power}}$

$\boxed{Q_E = 10 \Rightarrow 10\% \text{ Recirculating Power}}$

ICF targets are imploded by the rocket effect

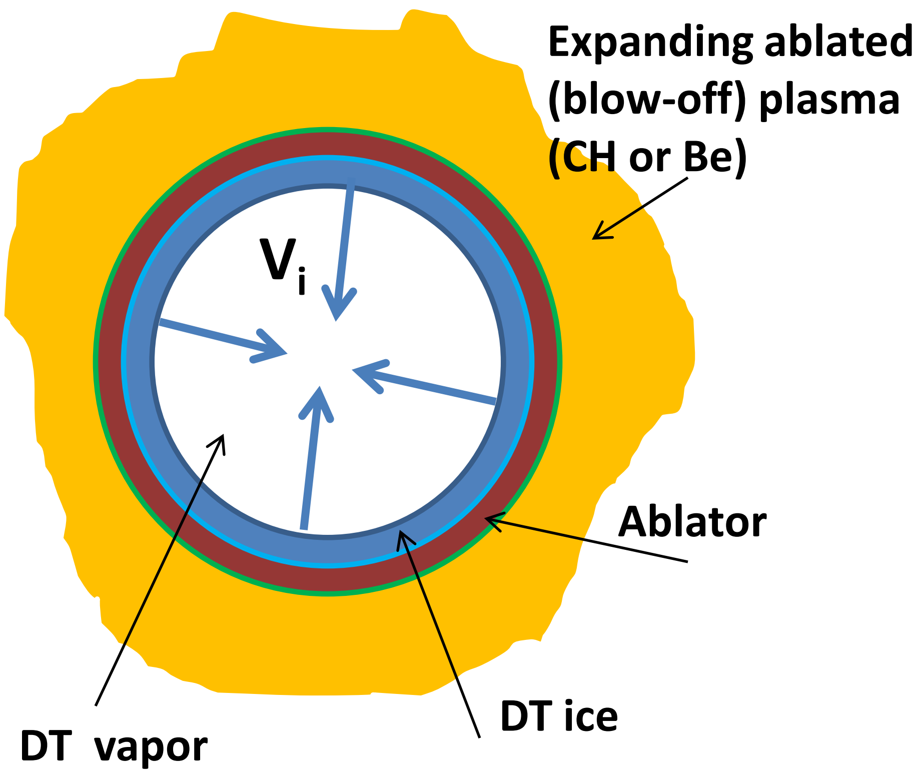




Implosion are driven by the rocket effect from the blow-off plasma.

Driving IFE targets is a very inefficient process

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



Examples:

NIF 1MJ Indirect Drive Point Design
Laser energy = 1MJ
Shell final kinetic energy = 17kJ
Total efficiency = 1.7 %

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

V_i = implosion velocity

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

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

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

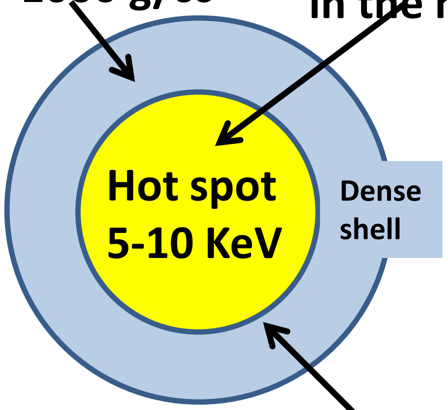
~50% → **Compression and heating of the central hot spot (equivalent to the MFE heating input energy <u>coupled</u> to the plasma)**

~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

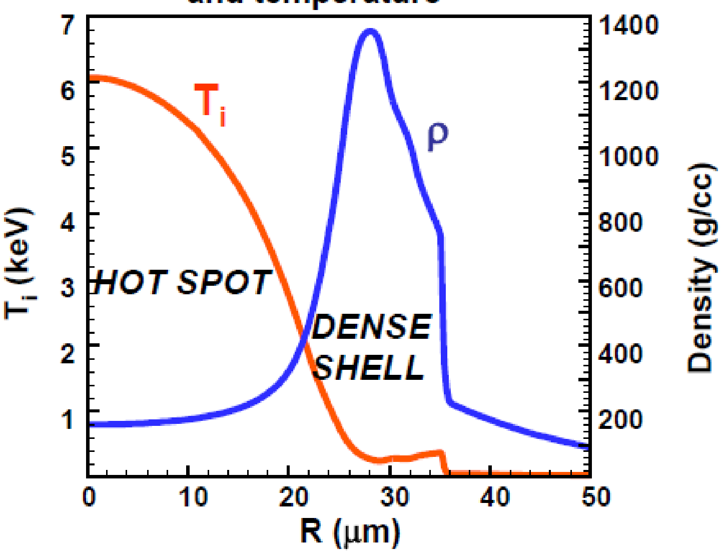
Ignition takes place in the hot spot



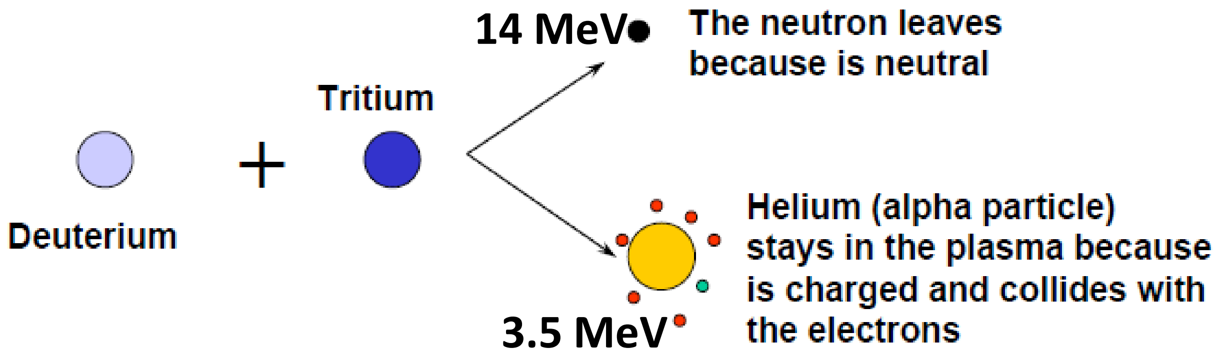
Provides the confinement of the hot spot (and more)

Stagnation density and temperature

(NIF-like, 1MJ)



Ignition takes place in the "hot spot." The thermonuclear instability (ignition) is triggered when the alpha self-heating exceeds all the energy losses in the hot spot



Ignition condition

alpha-power> power-losses

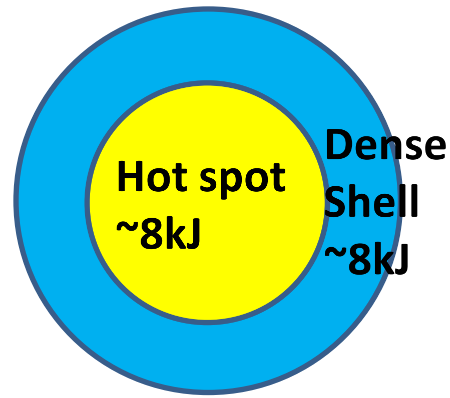
The plasma gets hotter and produces more fusion reactions leading to a thermal runaway

→ Thermonuclear instability → Ignition

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 (Still only physics here!)

Example:

- NIF 1MJ Indirect-Drive point design
- Total kinetic energy = 17kJ
- ~50% goes into the hot spot $E_{input\text{-}external}$ ~8kJ
- ~50% goes into the shell ~9kJ (to provide the confinement time τ required for ignition)



AMPLIFICATION DUE TO IGNITION

Consider (for example):

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

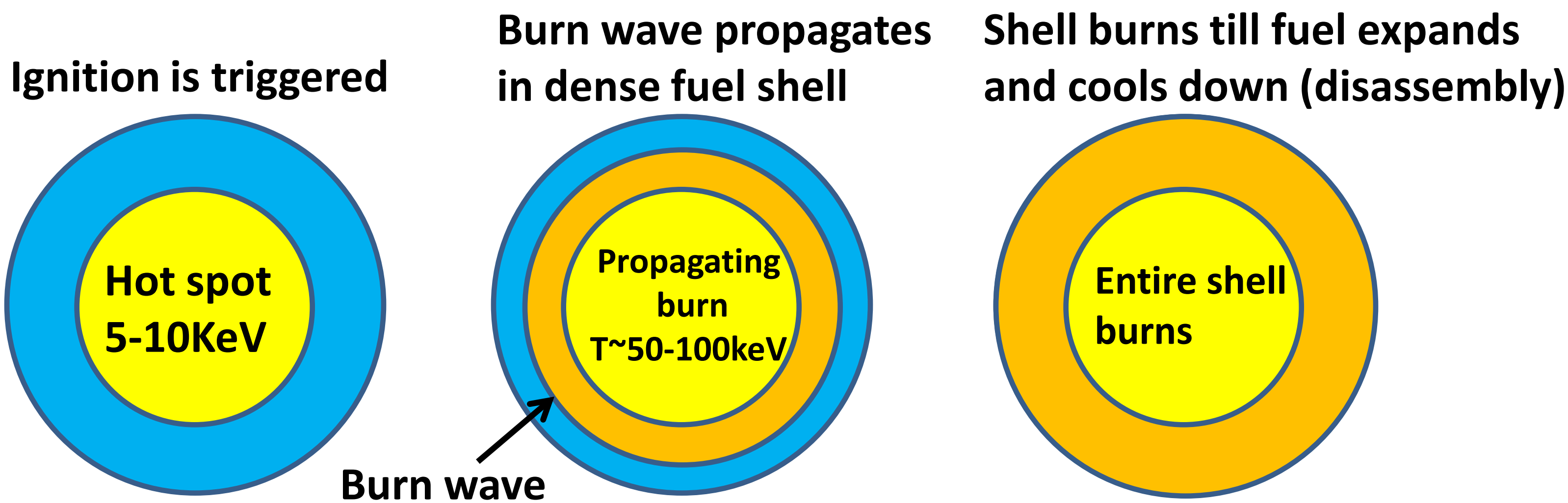
(b) PHYSICS thermonuclear $Q=E_{out}/E_{input\text{-}ext}$
$Q = 1MJ/8kJ=125$

(c) Self-heating level $Q_\alpha=E_\alpha/E_{input\text{-}ext}$
$Q_\alpha = Q/5=25$

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

A Q~100 may (arguably) 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 = 17kJ
- 8kJ into the hot spot

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

Consider a 20 MJ fusion yield

$$Q=20\text{MJ}/8\text{kJ}=2500$$

$$Q_\alpha = Q/5=500$$

From PHYSICS to ENGINEERING: The Target Energy GAINS =fusion-energy-output/driver-energy-on-target are ENGINEERING parameters of practical importance for energy

Energy Target Gain:

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

The GAIN is a useful engineering parameter but has no fusion-physics meaning.
The Driver energy delivered into the chamber is much greater than the energy <u>coupled</u> to the target as kinetic energy (<5% is coupled)

Compare to physics or thermonuclear Q:

$$Q = \frac{\text{Fusion Energy Output}}{\text{½ Driver Energy \underline{coupled} as kinetic energy}}$$

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

Gains for Ignition and Burn (<u>this is approximate within factors ~ 2</u>),

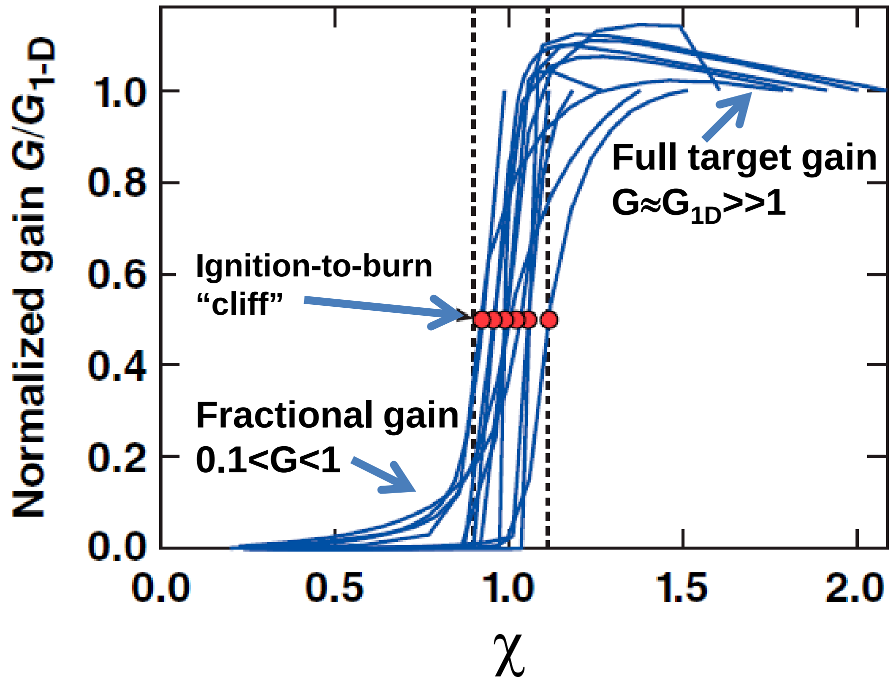
Example:
- **NIF 1MJ ID point design**
- **Total kinetic energy = 17kJ**
- **8kJ into the hot spot**

G ~ 0.1 → Q~ 10 → Burning plasma (α dominated but not very interesting in ICF)

G ~ 1 → Q~ 100 → Ignition has taken place

G ~10 → Q~1000 → Propagating burn has taken place

Small changes in the target performance determine the transition from fractional (ignition, G~0.1) to full target gains (burn propagation, G>>1)



ρR= areal density

T_I=hot spot temperature

$$\mathrm{YOC} \equiv \frac{\text{exp - yield}^{\text{no-burn}}}{\text{1D - yield}^{\text{no-burn}}}$$

Ignition/Lawson criterion for ICF → $\chi > 1$

$$\chi \equiv \frac{nT\tau}{[nT\tau]^{ignition}_{\text{min at T}}} \approx (\rho R_{g/cm^2})^{0.8} \left(\frac{T_{keV}}{4.7}\right)^{1.6} YOC^{0.4}$$

Demonstrations of Ignition and Burn (Gains>10) are required to validate the target physics for IFE. Each IFE concept will require its own "NIF" for validating the target physics.

- Achieving Gains>10 is a requirement for validating the target physics

- NIF could validate the target physics for Laser Indirect Drive and Laser Direct Drive (with upgrades to implement Polar Drive)

- Other IFE concepts can take advantage (at different levels) of laser-fusion ignition on the NIF and learn some relevant target physics.

- However, laser-fusion ignition does NOT validate all approaches to IFE. There are many aspects of target physics that need to be controlled and understood (symmetry, pre-heat, pulse shaping, energy coupling, hydro-instabilities…..and many more). Each driver exhibits different target physics.

- Each IFE concept will require a separate development path. Each approach will require its own "NIF" for validation of the target physics.

Commercial power production requires large Engineering Q's

$$Q_E = \frac{\text{Electric Power Out} = P_{out}}{\text{Electric Power In} = P_{in}} = \eta_D\, G\, A_B\, \eta_{th}$$

$$P_{out} = P_{in}\, \eta_D\, G\, A_B\, \eta_{th}$$

η_D =Driver Wall-Plug Efficiency = $\dfrac{\text{Electrical Driver Input per shot}}{\text{Energy into Target Chamber}}$

G=Target Gain

A_B =Blanket amplification ~ 1.1

η_{th} =thermal cycle efficiency

Q_E =1 electric power breakeven;
Q_E =10 → 10% recirculating power

High Target Gains are required for IFE

10% recirculating power	20% recirculating power	20% recirculating power
$Q_E = 10$	$Q_E = 5$	$Q_E = 5$
$\eta_D = 0.1$	$\eta_D = 0.1$	$\eta_D = 0.2$
$A_B = 1.1$	$A_B = 1.1$	$A_B = 1.1$
$\eta_{th} = 0.4$	$\eta_{th} = 0.4$	$\eta_{th} = 0.4$
$G \approx 230$	**$G \approx 115$**	**$G \approx 58$**

For reference: $\eta_{D(NIF)} = 0.0066$, $G \sim 15\text{-}20 \rightarrow Q_E \sim 0.05$
Note: NIF is a single-shot facility NOT designed for energy applications.
An IFE laser-driver would NOT be a glass laser but a high–efficiency diode-pumped or KrF

After the demonstrations of Ignition and Burn (Gains≥10), the next step in target physics is determining how to achieve IFE-relevant target gains (Gains≥60)

θ = burn-up fraction (fraction of the DT fuel mass that "fuses")
m_i = average DT ion mass
V_i = DT shell final implosion velocity
η_c= fraction of the driver energy coupled to the target (as final kinetic energy)
E_D= Driver energy into the target chamber

$$G = \frac{E_{fusion}}{E_D} = \frac{1}{2}\frac{M_{DT}\theta}{m_i}\frac{\varepsilon_{fusion}^{17.5MeV}}{E_D} = \frac{\theta}{m_i}\frac{1}{2}\frac{M_{DT}V_i^2}{V_i^2}\frac{\varepsilon_{fusion}^{17.5MeV}}{E_D}$$

$$G = \frac{\theta}{m_i}\frac{\varepsilon_{fusion}^{17.5MeV}}{V_i^2}\frac{E_{kinetic}^{shell}}{E_D} = \frac{\theta}{m_i}\frac{\varepsilon_{fusion}^{17.5MeV}}{V_i^2}\frac{\eta_c E_D}{E_D}$$

$$\boxed{G = \frac{\theta}{m_i}\frac{\varepsilon_{fusion}^{17.5MeV}}{V_i^2}\eta_c}$$

Assumes that Ignition has taken place

Note: while designing the target to increase the gain one needs to make sure that the ignition condition is satisfied

There is a minimum shell kinetic (and therefore driver energy) below which ignition fails. Below is the minimum energy (for an ideal 1D implosion)

For ignition[1] →

$$\boxed{E_{Driver} > \frac{E_{kinetic}^{min-ign}}{\eta_c} \approx \frac{50(kJ)}{\eta_c}\alpha^2\left(\frac{300}{V_i(km/s)}\right)^6\left(\frac{100}{P(Mb)}\right)^{0.8}}$$

α = shell entropy = P(Mbar)/2.2 ρ(g/cc)$^{5/3}$

P = pressure applied by the driver on the shell

V_i = DT shell final implosion velocity

η_c= fraction of the driver energy coupled to the target (as final kinetic energy)

[1] Herrmann, Tabak, Lindl, Nuc Fusion 41, 99 (2001)

Increasing the gains by using bigger targets and larger drivers

$$G = \frac{\theta}{m_i} \frac{\varepsilon_{fusion}^{17.5MeV}}{V_i^2} \eta_c$$

- **Increase the burn-up fraction θ with larger drivers**

$$Gain \sim \theta \qquad \theta \approx \frac{\rho R}{\rho R + 7g/cm^2} \qquad \rho R \sim E_D^{1/3}$$

- **Decrease the implosion velocity by increasing the fuel mass**

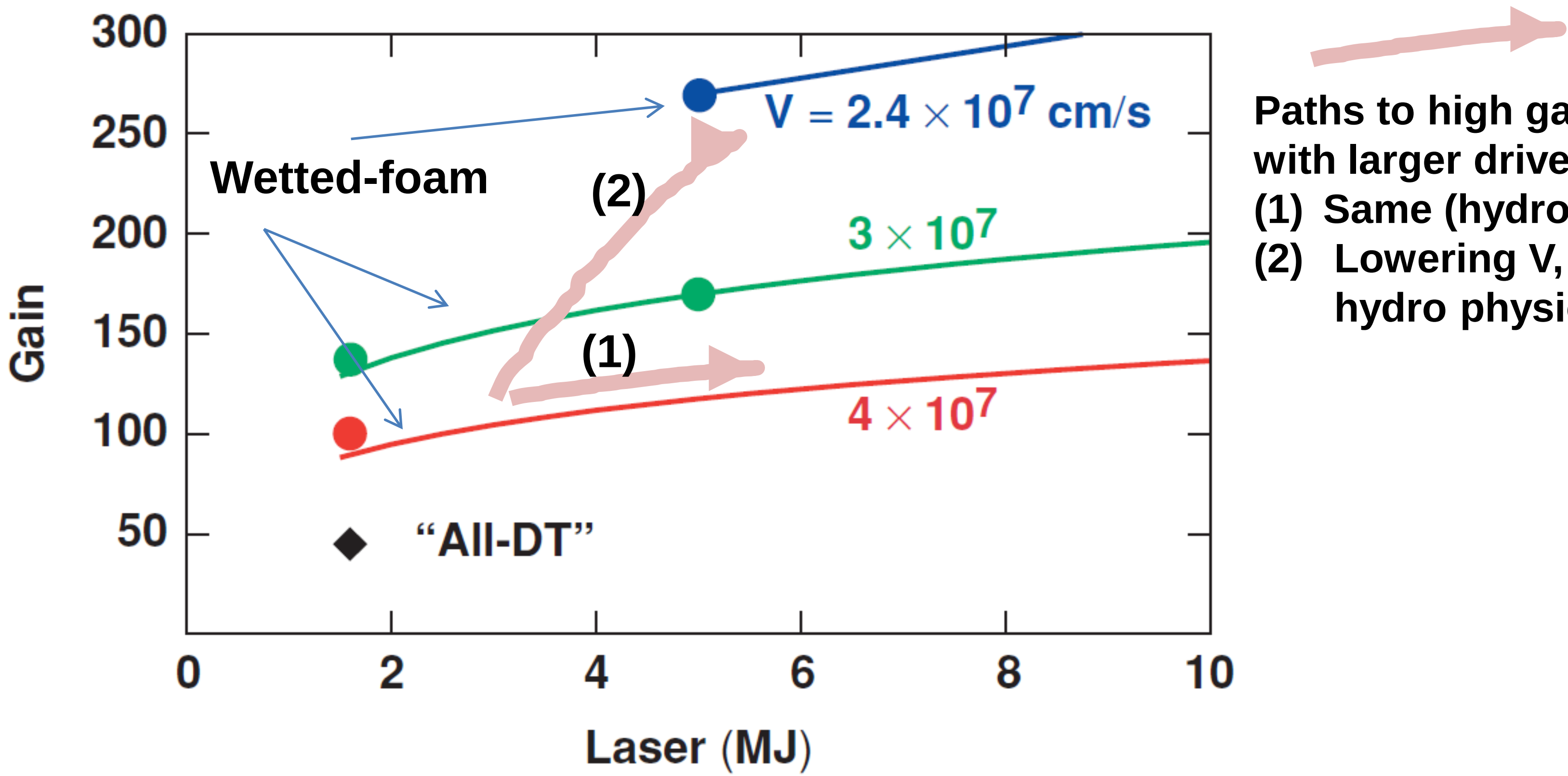
$$Gain \sim 1/V_i^{1.3-2}$$

Since ignition fails below a critical V_i, this will also require larger drivers given that

$$E_{ignition}^{\min} \sim 1/V_i^6 \qquad Gain \sim E_D^{0.2-0.3}\theta(E_D^{0.3})$$

The Target Gain is a weak function of the driver energy for a fixed implosion velocity. Need lower V for high gains

UV (λ_L=0.35μm) direct-drive gains (Skupsky LLE)



Paths to high gains with larger drivers
(1) Same (hydro) physics
(2) Lowering V, different hydro physics

Physics (hydro) equivalent implosions have equal velocity. Lowering the velocity leads to higher gains but ignition will fail below a critical velocity (different implosion physics)

Increasing the gains by lowering the target entropy

$$G = \frac{\theta}{m_i} \frac{\varepsilon_{fusion}^{17.5MeV}}{V_i^2} \eta_c$$

- **Increase the burn-up fraction θ by lowering the entropy α**

$$Gain \sim \theta \qquad \theta \approx \frac{\rho R}{\rho R + 7g/cm^2} \qquad \rho R \sim \frac{1}{\alpha^{0.6}}$$

- **Decrease the implosion velocity (i.e. add more fuel mass) required for ignition by lowering the entropy**

$$Gain \sim 1/V_i^{1.3-2} \qquad E_{ignition}^{\min} \sim \alpha^2 / V_i^6$$

$$Gain \sim \frac{1}{\alpha^{0.4-0.6}} \theta(\alpha^{0.6})$$

- **The entropy can only be lowered if the hydrodynamic instabilities can be controlled**

Increasing the gains by shortening the laser wavelength for a fixed energy-on-target or by making more driver energy available using longer laser wavelengths

$$G = \frac{\theta}{m_i}\frac{\varepsilon_{fusion}^{17.5MeV}}{V_i^2}\eta_c$$

•For a fixed energy on target: →

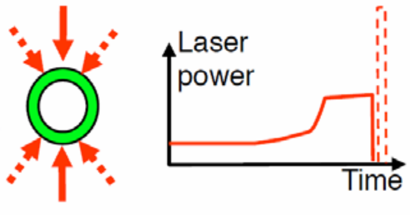
Green light → Lowest gains
UV light → Higher gains
Deep UV (KrF)
with zooming → Highest gains

$$Gain \sim \frac{1}{\lambda_{Laser}^{0.5}}$$

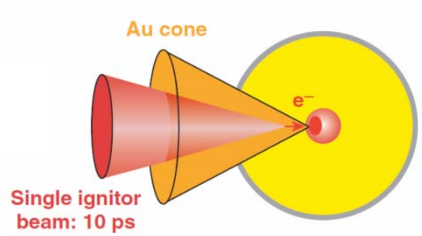
- **However, in solid state lasers, the laser energy on targets ~ doubles by shifting from blue to green thus effectively increasing the gain (…more like doubling the wall-plug efficiency)**

- **Caution! Green light is more effective in exciting laser-plasma instabilities. It has not been proven that green light can be used for IFE applications**

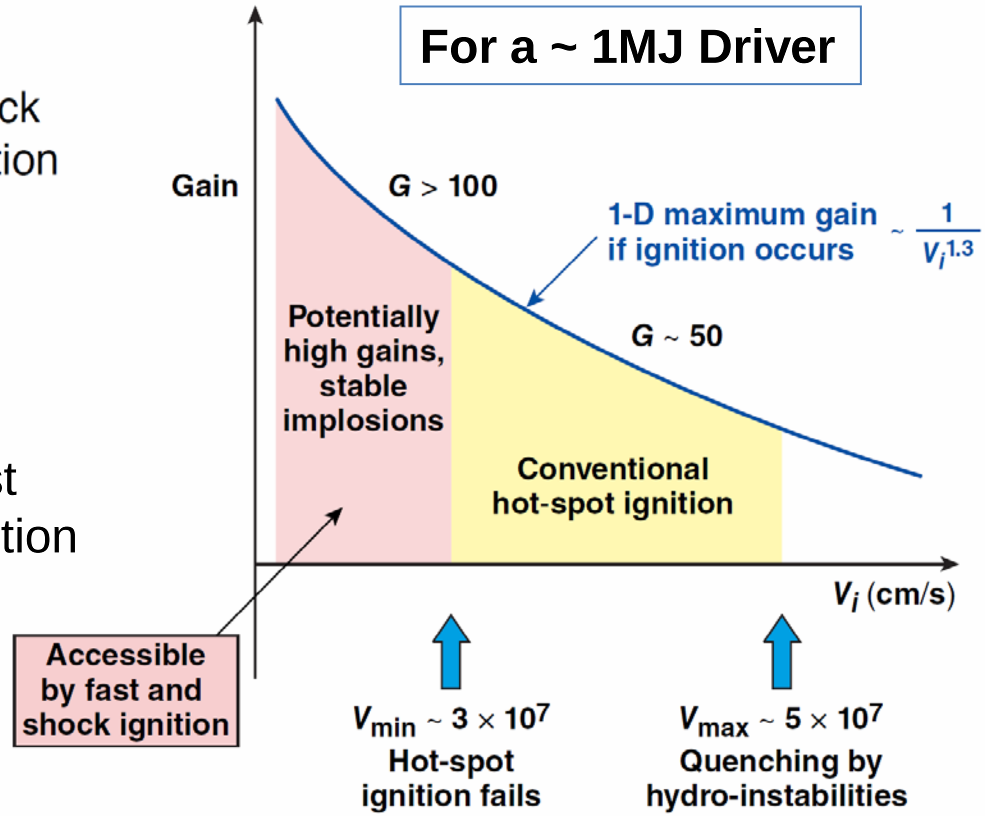
Increasing the gains by using alternative ways for triggering ignition



Shock
Ignition

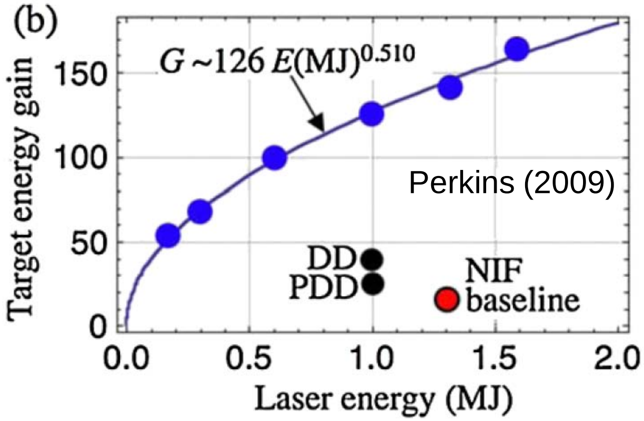


Fast
Ignition

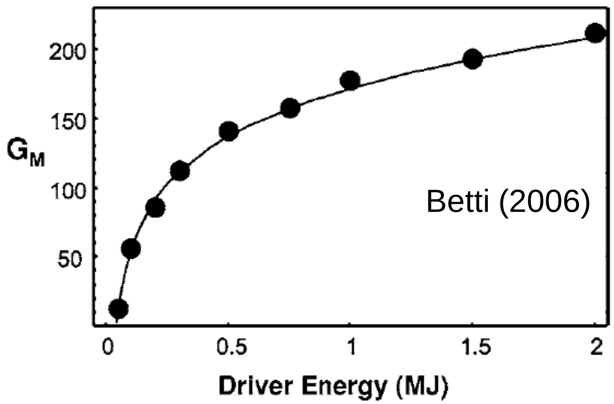


Gains > 100 are predicted for shock and fast ignition for driver energies of about 1MJ

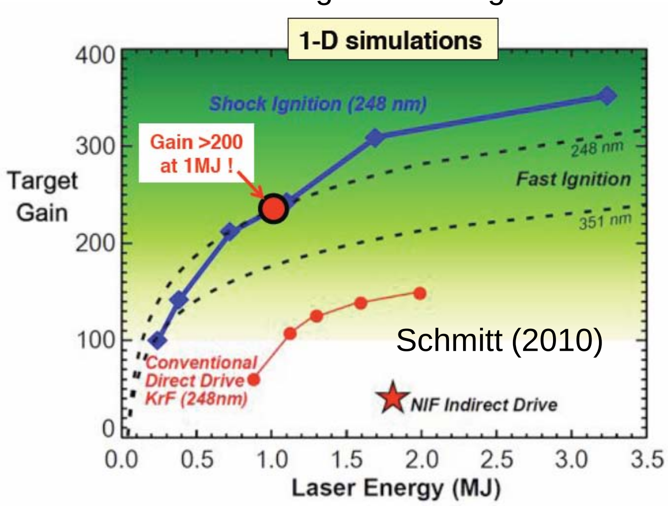
Shock Ignition max gains for NIF
(assumes 1D implosions)



Fast Ignition max gains for UV (0.35µm)
(assumes 1D and negligible energy in short pulse)



Shock and Fast Ignition max gains for KrF

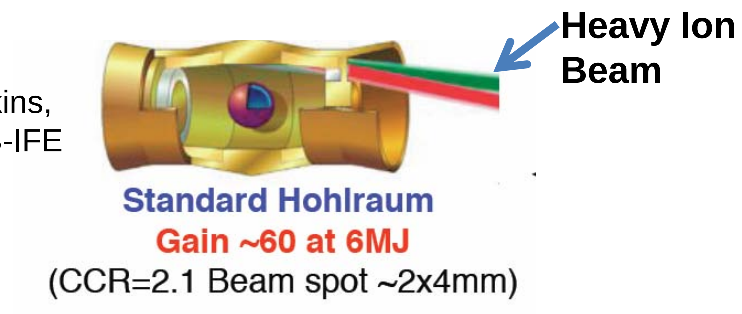


Shock Ignition uses hydrodynamic shocks to ignite the hot spot → simple physics.
STATUS: Some design work but poor experimental basis.
<u>VALIDATION: Could be tested on the NIF in Polar Drive</u>

Fast Ignition uses particles acceleration from high intensity short-pulse lasers → complex physics.
STATUS: Significant worldwide effort but uncertain experimental basis.
<u>VALIDATION: Requires NIF + >100kJ new short pulse laser</u>

Increasing Q_E by using more efficient drivers: heavy ion accelerators and electromagnetic drivers

Perkins, NAS-IFE

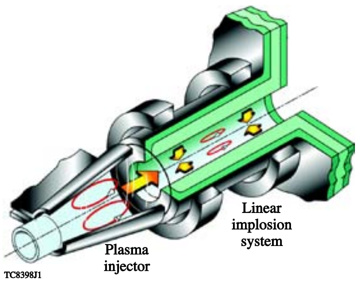


HIF offers the potential of high wall-plug efficiency ~ 30-35%
(as advertised)

Perkins, NAS-IFE

Z-pinch fusion offers the potential of high wall-plug efficiency ~ 70%
(as advertised)

Wurden, This meeting



Magnetized Target Fusion offers the potential for high wall-plug efficiency (but low target gains)

Conclusions

- **Target Gains ≥ 10 are required to validate the target physics of central (or hot spot) ignition IFE**
- **Target Gains ~ 1 imply ignition but this is not sufficient for IFE**
- **NIF has the potential to validate the target physics for laser fusion (both indirect and direct drive)**
- **Other IFE concepts can learn from NIF ignition but will require their own ignition facility to validate the target physics**
- **New implosion/ignition schemes offer the potential to raise the target gains without increasing the driver energy (shock ignition and fast ignition)**
- **Switching from blue to green light improves the wall-plug efficiency ……. but watch for laser-plasma instabilities!**
- **Heavy Ion Accelerators or Electromagnetic drivers have higher wall-plug efficiency than lasers**