How ICF targets implode to the conditions exceeding those of the center of the sun, in order to achieve fusion ignition: A mini tutorial

Mordecai D. ("Mordy") Rosen

248th ACS National Meeting & Exposition 8/11/14 San Francisco, CA

Lawrence Livermore National Laboratory

rosen2@llnl.gov

LLNL-PRES-658079

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

The goals of this talk

To present the basics of ICF

To put our expectations of NIF target performance into that context

To (…try to …) balance simplicity with quantitative results

To briefly review what (some of) the current challenges are

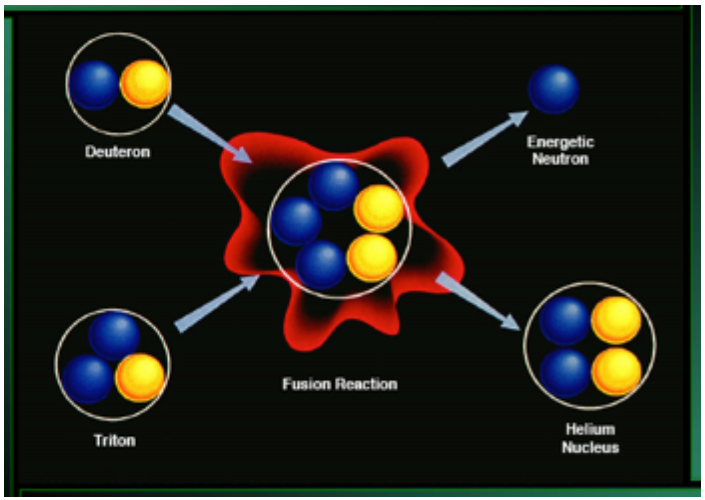
and

To reflect on what an impressive neutron source NIF already is

Coulomb barrier makes high temperatures necessary for DT thermonuclear fusion

D

T

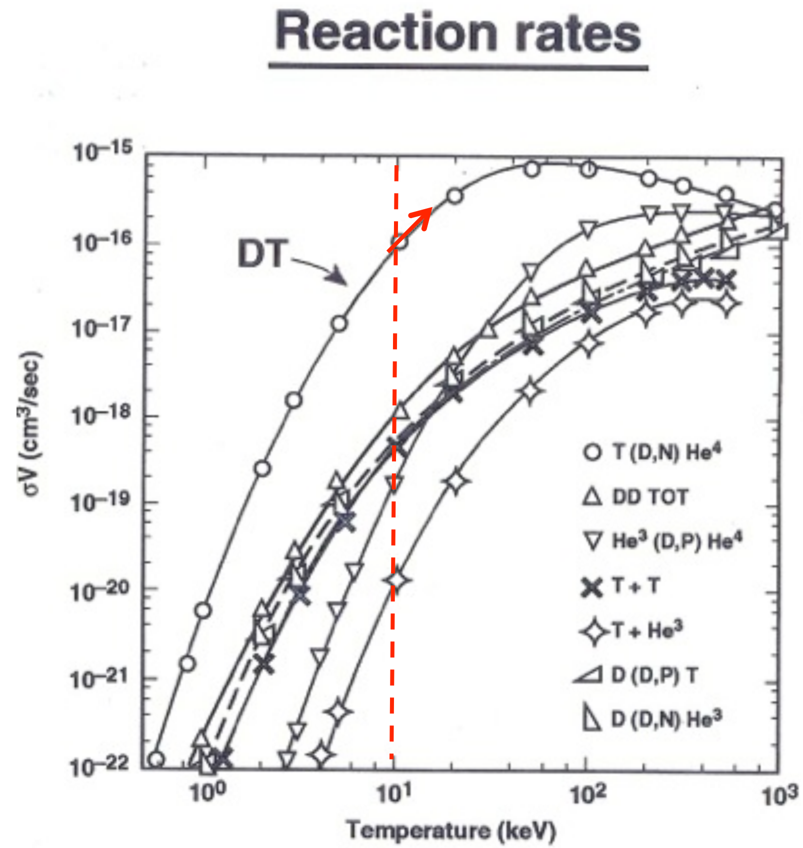


n

α

D + T   α + n

3.5 MeV   14.1 MeV



$$Q_{fusion} = 3.3\ 10^{14}\ J / kg$$

“Nature’ s Gift”

What is "inertial confinement"?

Inertial confinement is the minimal form of confinement — the fuel is confined only by its own inertia ⇒ How long until it falls apart?

mass averaged confinement time

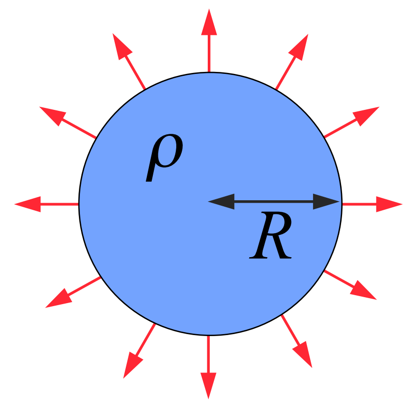
$$\langle \tau_c \rangle \cong \frac{1}{M}\int_0^R \rho \frac{R-r}{c_s} 4\pi r^2 dr$$

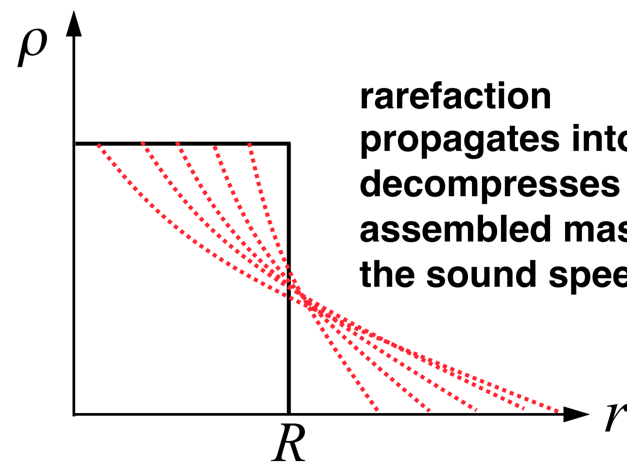
local con-
finement time

$$= \frac{4\pi \dfrac{\rho}{c_s}\left(\dfrac{R r^3}{3} - \dfrac{r^4}{4}\right)\Bigg|_0^R}{\dfrac{4\pi}{3}\rho R^3}$$

$$= \frac{R}{4c_s}$$

most of the mass is at large radius





rarefaction propagates into and decompresses the assembled mass at the sound speed c_s

The burn fraction is determined by the "areal density" ρR

fusion burn rate

$$\frac{dn_T}{dt} = -n_T n_D \langle \sigma v \rangle \quad \& \quad n_T = n_D = \frac{n}{2}$$

$$\Rightarrow \quad \frac{dn}{dt} = \frac{-n^2}{2} \langle \sigma v \rangle$$

burn fraction

$$f \approx \frac{\tau_{conf}}{\tau_{burn}} = \frac{n\langle \sigma v \rangle R}{2 \bullet 4 c_s} = \frac{\rho R}{8\, m_i\, c_s / \langle \sigma v \rangle} \cong \frac{\rho R}{90\ \mathrm{kg/m^2}} \quad , \quad @T_i = 30\ \mathrm{keV}$$

Require $\rho R \geq 30\ \mathrm{kg/m^2}$ for $f \geq 1/3$

"30"/"30" in MKS

A reasonable fuel mass requires high fuel compression (~ factor of > 1000)

Spherical imploded mass

$$f \sim 1/3 \quad \Rightarrow \quad \rho R \cong 30.\,\mathrm{kg/m^2} \quad \Rightarrow \quad M = \frac{4\,\pi}{3}\rho R^3 = \frac{4\,\pi}{3}\frac{(\rho R)^3}{\rho^2}$$

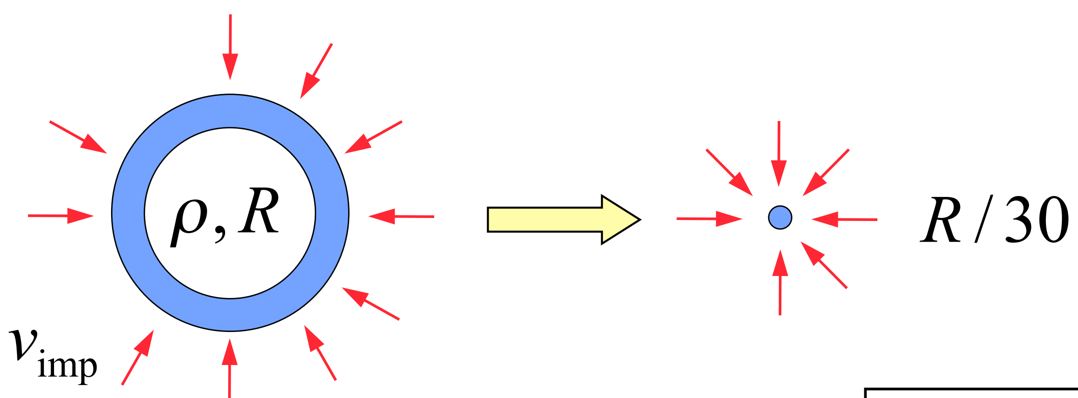
$\rho(\mathrm{kg/m^3})$	$R(\mathrm{m})$	$M(\mathrm{kg})$	$Y(\mathrm{MJ}) = \mathrm{f\,MQ_{fus}}$
250	**0.12**	**1.8**	**1.8×10^8** **~ 43 kilotons TNT!**
NIF **1,000,000**	**0.00003**	**1.2×10^{-7}**	**13**

Achieving such high densities requires spherical compression by $R_i / R_f > 10$

Exploit R^3 compression with spheres

$$M = \frac{4\pi}{3}\rho_{\text{initial}}\, R_{\text{initial}}{}^{3} = \frac{4\pi}{3}\rho_{\text{final}}\, R_{\text{final}}{}^{3} \quad \Rightarrow \quad \frac{\rho_{\text{final}}}{\rho_{\text{initial}}} = \left(\frac{R_{\text{initial}}}{R_{\text{final}}}\right)^{3}$$

In practice, we accelerate a hollow shell (with 20% of the initial mass) inward to high velocity ⇒ require convergence of ~ 30

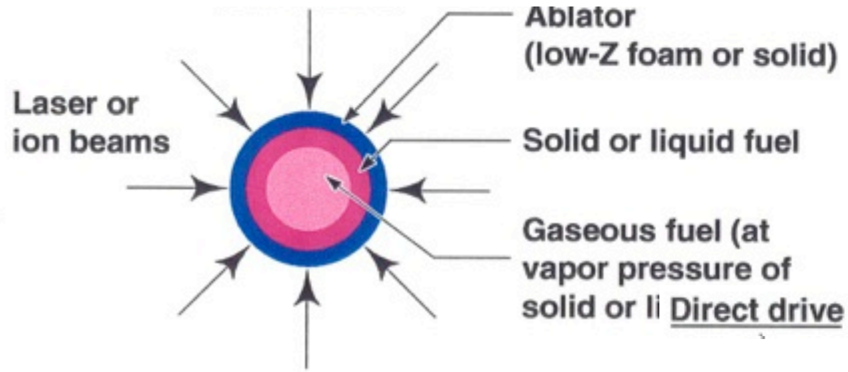


NIF: $R_{\text{initial}} = 1\ \text{mm} \Rightarrow R_{\text{final}} = 30\ \mu\text{m}$

Symmetry is a big issue !

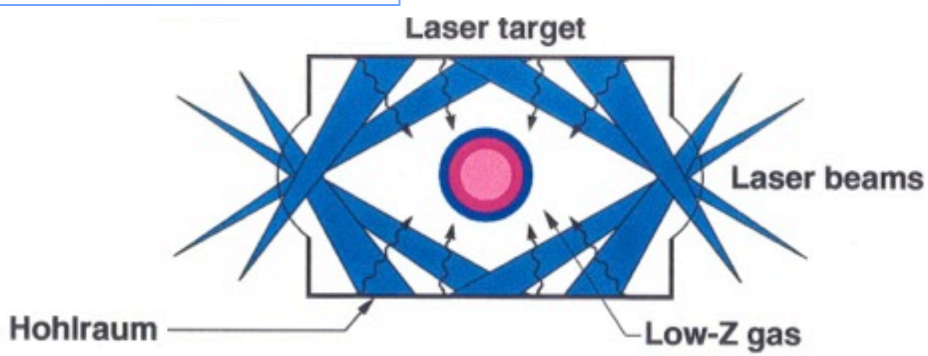
The two principal approaches to ICF are direct drive and indirect drive

Direct drive



Advantage:
- Higher coupling efficiency

Indirect drive

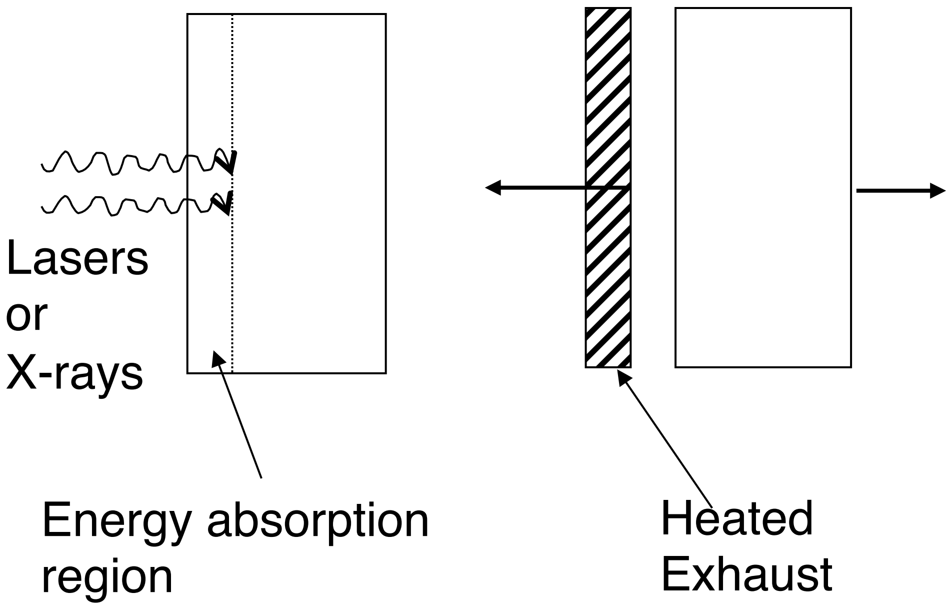


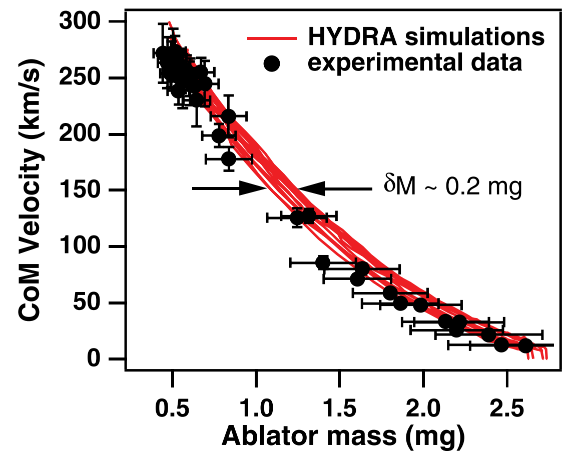
Advantages:
- Relaxed beam uniformity
- Reduced hydrodynamic instability
- Significant commonality for lasers and ion beams

Actually, ICF *is* rocket science!

- **Rocket-like reactions.**

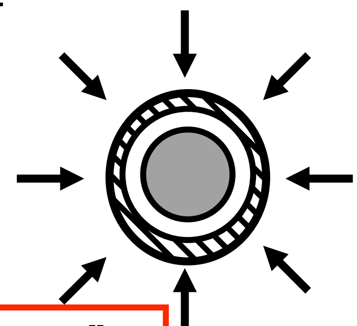
$$V_{imp} = V_{exh} \ln (m / m_0)$$





Meezan et al PoP 20, 056311 ('13)

For a capsule this takes place in spherical geometry

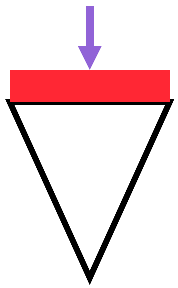


For indirect drive, to maximize "rocket efficiency", the payload is at an optimal mass fraction of ~ 20%

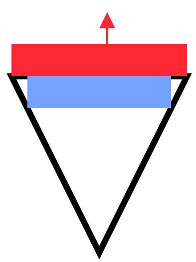
Summary of energy flow in ICF implosions

- Driver energy E_D

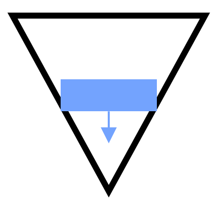
- E_{cpl} = coupled energy.
- $E_{CPL} = \eta_C E_D$



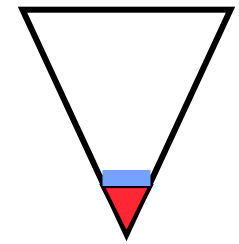
- Thermal and
- kinetic energy



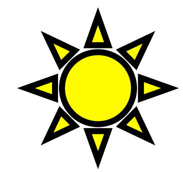
- K.E. = $\eta_H E_{CPL}$. $E_{KE} = \eta_H \; \eta_C \; E_D$



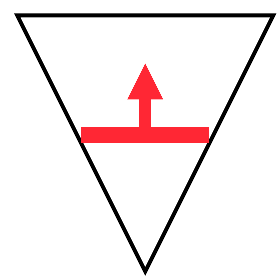
- Assembled Thermal Energy
- $E_{AF} = \eta_{AF} \; \eta_H \; \eta_C \; E_D$



- Thermonuclear burn



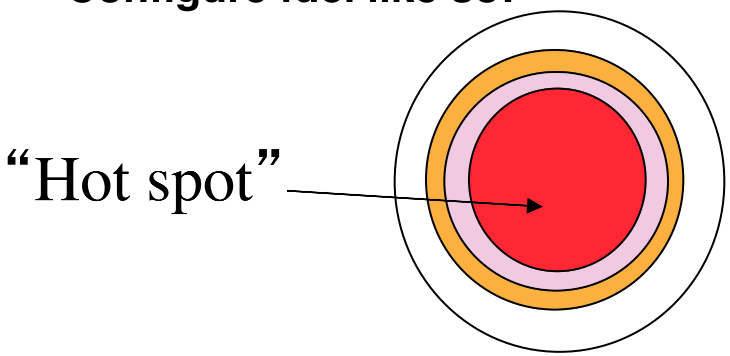
- Dis - assembly

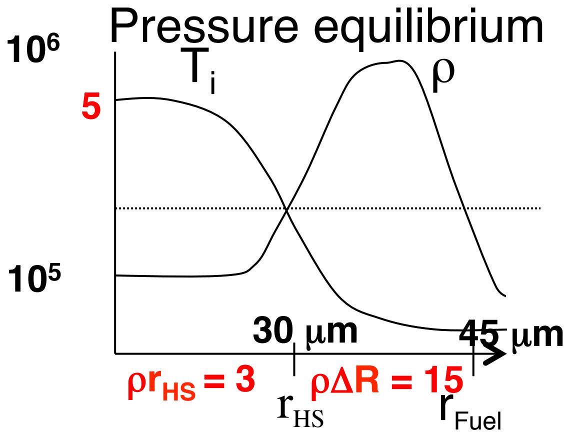


LLNL-PRES-658079

To get high gain on NIF, let fusion itself do the heating: hot spot ignition and propagating burn

Configure fuel like so:





- **Hot spot heated by PdV compressive work to ~ 5 keV.**
  - **It has only a small fraction of the mass.**
- **Alpha particles stop in hot spot and raise T to ~ 10 keV. Then more alphas from hot spot stop in surrounding cold dense fuel**
  - **heat up an annular shell of DT to 5 -10 keV (while neutrons fly out)**
- **Annular shell fuses, & its alphas heat the next shell of DT: a propagating thermonuclear burn wave.**
- **Thus, (1/5 of) fusion itself does the heating. This leads to high gain.**
  - **What are the necessary conditions for the hot spot?**
  - **How much energy does it take to simply compress DT without heating it?**

Ignition physics:

Heating

- **PdV work done on gas during implosion;**
- **α heating**

- **Need: $\rho_{hs} R_{hs} \approx$ range of $\alpha \approx 3\ kg/m^2$ (@ 10 keV) for hot spot to boot-strap from 5 to 10 keV.**

Cooling

- **electron conduction,**
- **rad losses (need $T > 4$ keV to overcome bremsstrahlung losses)**
- **PdV work done by gas during explosion**

For a non ideal implosion, heating time scales can be stretched by:

Incomplete stagnation: lessens PdV heating rate

Perturbed shell interface: more area for conductive losses

Mix of cold fuel into hot spot lowers T.

Mix of CH ablator into hot spot supplies higher Z: increases rad losses

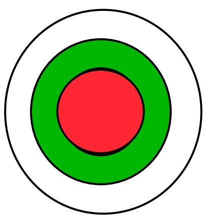
This stretched time scale means we can lose the ignition game of "beat the clock"

Ignition criteria: $\rho_{hs}\, R_{hs} \approx 3\ kg/m^2$ & $T_{hs} = 5\ keV$

- **Hot spot must be large enough to supply alpha's for next shell of high density material (with $\rho\Delta R$ of 3) to heat it to 5 (and then 10) keV.**
  - **That shell has 3x the mass of the hot spot:**

H.S. **vs.** **Next Shell ("N.S.")**

$$\frac{4}{3}\pi\,\rho_{hs}R_{hs}^{3} = 4\pi R_{hs}^{2}\left(\frac{\rho_{hs}R_{hs}}{3}\right) \qquad 4\pi R_{hs}^{2}\left(\rho_{ns}\Delta R_{ns}\right)$$



Claim: $\rho_{hs}\ R_{hs} = 3$ *again* does the trick! Because $\Rightarrow f_b \approx 3\%$

- **$E_{\alpha HS} = (3.6\ MeV\ _{DT})\ f_b\ (M_{HS} / m_{DT}) = 108\ keV\ (M_{HS} / m_{DT}) = 36\ keV\ (M_{NS} / m_{DT})$.**
- **$E_{10keVNS} =$ (3/2) (5 keV) (4 particles per DT) $(M_{NS} / m_{DT}) = 30\ keV\ (M_{NS} / m_{DT})$**

$\therefore$ $E_{\alpha HS}$ enough to heat the mass of the shell next to the hot spot

What is the energy needed to compress the fuel?

- We must do work against quantum back-pressure in order to compress the electrons.
  - Fermions - only 1e is allowed per state.
- Particles squeezed closer together increase their momentum,
  - their kinetic energy will increase,
  - creating a "back-pressure" to cold compression.

$$\mathrm{K.E.} \approx \frac{p^2}{2m} \approx \frac{h^2}{2m}\frac{1}{(\Delta x)^2} \approx \frac{h^2}{2m}\frac{1}{(V/N)^{2/3}} \approx \varepsilon_F$$

$$E_{tot} = N\varepsilon_F \qquad \therefore P \sim \frac{E}{V} \sim \frac{h^2}{2m}\left(\frac{N^{5/3}}{V^{5/3}}\right) \sim C\rho^{5/3}$$

- For DT:

$$P_{FD}(\mathrm{Pa}) = 2.2 \bullet 10^6 \alpha\rho^{5/3} \qquad E_{FD}(\mathrm{J}) = 3.3 \cdot 10^6 \alpha\, \rho_{DT}^{2/3} M_{DT}(\mathrm{kg})$$

The minimum value of α is 1 for matter which is Fermi degenerate

With α s from hot spot / propagating burn wave now doing the heating, gain can be much higher

Energy pay-off from fusion = "Q" = E_F / M = $3.3\ 10^{14}$ (J/kg)

Energy investment in cold- compression = E_C / M_C = $\alpha\ 3.3\ 10^6\ \rho_C{}^{2/3}$ (J/kg)

So for $\rho_C = 10^6$ kg/m^3, Inherent Gain = $10^4 / \alpha$

<u>Scaling:</u>

Larger energy drivers can have larger R (but cost more $)

Larger R requires less ρ to achieve the required ρR product.

Lower ρ leads to higher Gain.

We can now estimate that the anticipated Gain from NIF will be ~ 10

Scale	$1/\alpha$	$10^4/\rho_6^{2/3}$	η_C	η_H	η_{AF}	f_B	G
NIF	**1.0**	$10^4/$**1.0**	**0.1**	**0.1**	**0.5**	**0.2**	**10**

What implosion velocity is required to achieve the required fuel assembly?

$$\eta_{AF} KE = \frac{1}{2} \mathrm{KE} = \frac{1}{2}\frac{1}{2} \mathrm{M_C V_{imp}^2} = \mathrm{E_C}$$

1/2 represents Imperfect implosion - (need to build in "margin")

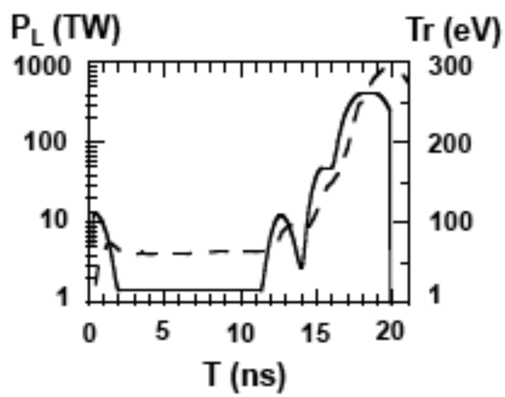
Then $V_{imp}^2 = 4 (E_C / M_C) = 4 \times 3.3\ 10^6\ \rho_C^{\ 2/3}$

So for $\rho_C = 10^6$, $V_{imp} = 3.6\ 10^5$ m / s

- **With $R_f = 30\ \mu$m, & a CR = 30 , this implies $R_0 = 1$ mm**
- **Then expect an implosion time of t = 1 10^{-3} / 3 10^5 = 3 ns**
- **Then power required is 1.5 MJ / 3 ns = 500 TW**

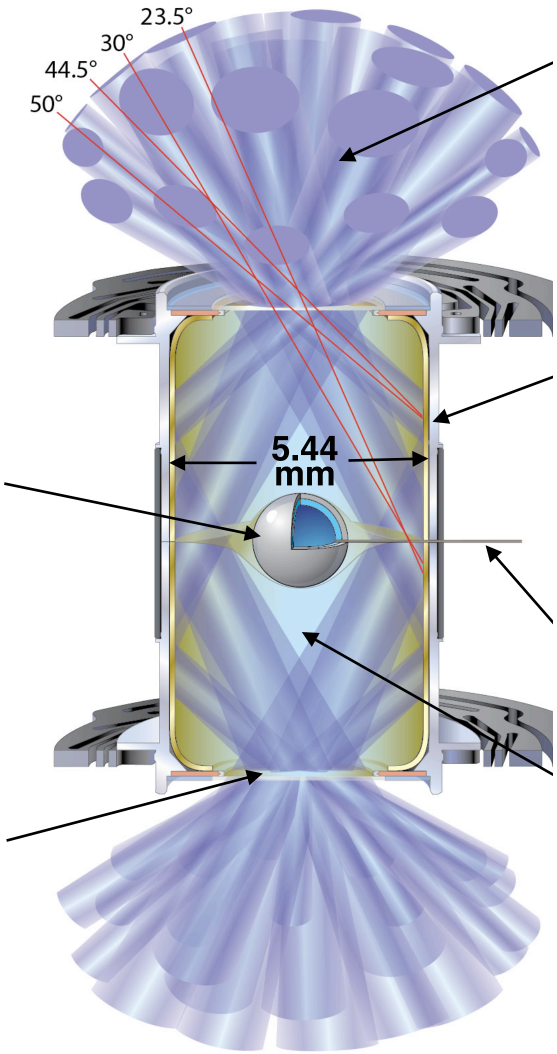
The NIF ignition design

Main pulse:
500 TW
3 ns



1 mm radius **Capsule with low-z ablator (CH, Be, or HDC*) and cryo DT fuel layer**

Laser Entrance Hole sized to balance LPI and radiative losses – 56–60% of LEH diameter



***High Density Carbon**

LLNL-PRES-658079

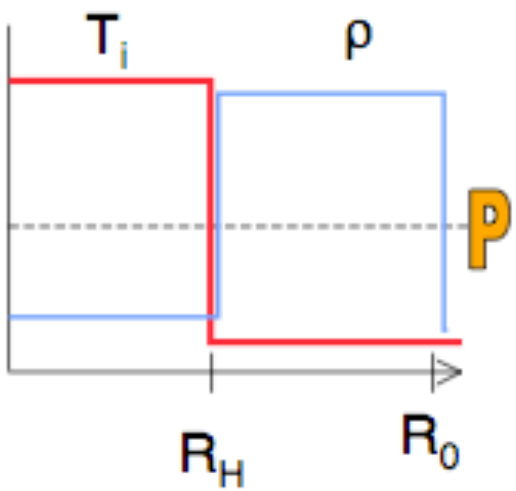
Example: NIF “gain 10” target assembly

Start with 1.3 MJ of NIF laser light

- **Assume indirect drive:** $\eta_c = 0.12, \eta_h = 0.11$ **, so assembled fuel has E_{tot} = 0.017 MJ (but part of “payload” is “left-over” ablator: ⇨ 11 kJ in DT)**
- **Distribute the fuel into a hot spot (with T = 5 keV, and ρR = 3 kg/m^2) and cold Fermi degenerate fuel ($\alpha = 1$) , in pressure equilibrium .**
- **<u>Assume</u> R_H= 25 μm = 2.5 10^{-5} m.**
- **Implies ρ_H = 1.2 10^5 kg/m^3 (so that $\rho_H R_H$ = 3 kg/m^2)**

$$M_H = \frac{4}{3}\pi\rho_H R_H^3 = 8\cdot 10^{-9}\,\mathrm{kg}$$

$$E_H = (2)\left(\frac{3}{2}\right) N_i kT = 4\cdot 10^3\,\mathrm{J}$$



Now for the NIF cold fuel & Gain calculation

- **Pressure:** $$P_H = (2)n_i kT = 2\left(\frac{\rho_H}{4.2\cdot 10^{-27}}\right)\left(5\cdot 10^3 1.6\cdot 10^{-19}\right) = 4.5\cdot 10^{16}\,\mathrm{Pa}$$
- **Pressure Equilibrium** $$\Rightarrow P_H = P_C = 2.2\cdot 10^6 \rho_c^{5/3} \Rightarrow \rho_c = 1.5\cdot 10^6 \mathrm{kg/m^3}$$
- **Cold Fuel: Recall that** $$E_{DT} = (E_{tot} - E_{un\text{-}abl}) = (17-6)10^3(\mathrm{J}) = 11KJ$$

$$E_c = E_{DT} - E_H = 11KJ - 4KJ = 7KJ$$

$$E_c = 3.3\cdot 10^6 \rho_c^{2/3} M_c \Rightarrow M_c = 1.7\cdot 10^{-7}\mathrm{kg}$$

$$\frac{4}{3}\pi\rho(R_F^3 - R_H^3) = M_c \Rightarrow \rho\Delta R_c \approx 15\mathrm{kg/m^2}$$

$$\Rightarrow f_b = \frac{\rho\Delta R_c}{\rho\Delta R_c + 70} \approx 0.2$$

$$\mathrm{Gain} = \frac{f_b M_c Q_{DT}}{E_{Driver}} = \frac{0.2\left(1.7\cdot 10^{-7}\mathrm{kg}\right)\left(3.3\cdot 10^{14}\mathrm{J/kg}\right)}{1.310^6\mathrm{J}} = 9$$

Y = 12 MJ

What neutron flux do we expect from a successful NIF ignition target?

- R_f = 30 μm, & $C_s = 10^6$ m/s , implies t_0 = 10 psec
- Y = 10 MJ implies 4 10^{18} neutrons
- Production rate: 4 10^{29} neutrons / sec
- Near target center: Fluence is:
  - 4 10^{26} neutrons / m^2
  - And Flux is:
    - 4 10^{37} neutrons / m^2 sec

This could well be the “killer app” for NIF science

So where are we now at NIF?

For hot spot ignition we need $\rho_H R_H$ = 3 kg/m^2 ,

If R_{HS} = 30 μm = 3 10^{-5} m, ⇨ ρ_H = 1.0 10^5 kg/m^3

We also need a T_{HS} ~ 5 keV

⇨ **Pressure:** $P_H = (2)n_i kT = 2\left(\frac{\rho_H}{4.2\cdot 10^{-27}}\right)\left(5\cdot 10^3\cdot 1.6\cdot 10^{-19}\right) = 4.0\cdot 10^{16}\ \mathrm{Pa}$

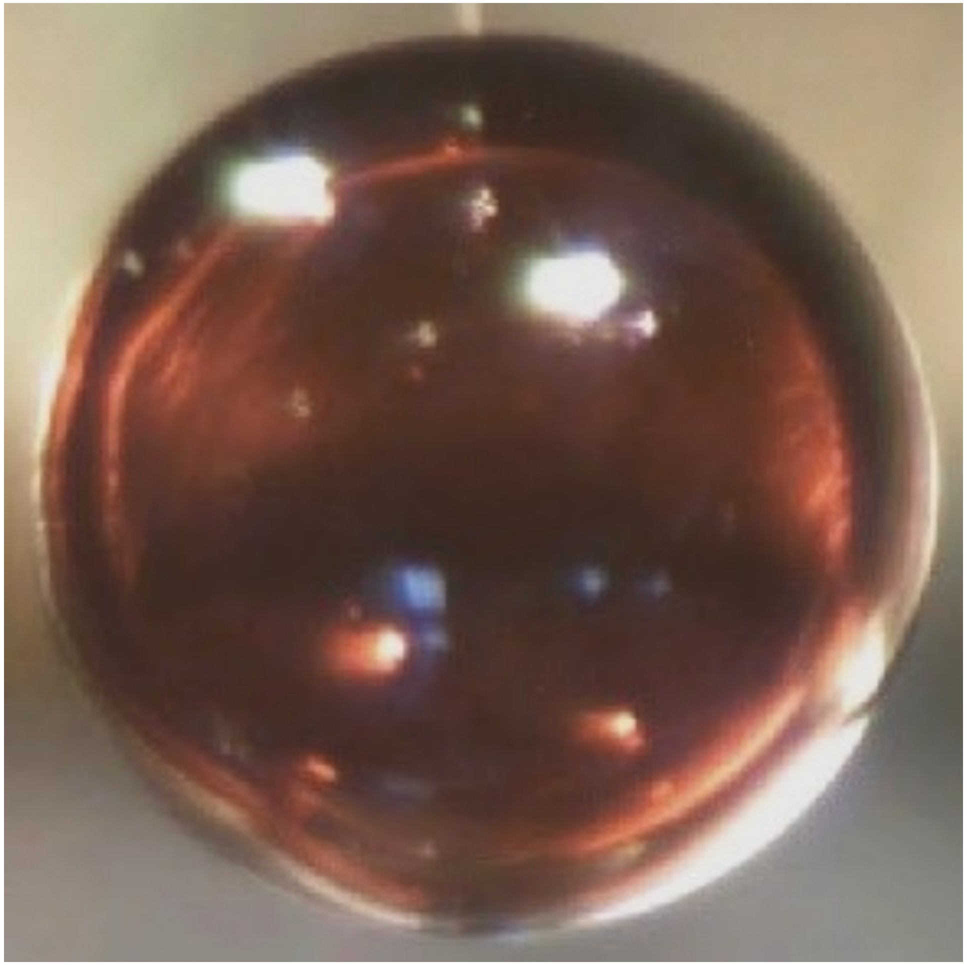
Analysis of Yield data* implies we are ~ 2 - 3 x *below* this 400 GB pressure

At present, non-spherical imploded shape is a serious contender for being the main "spoiler"

There may be other effects in play too, such as electron preheat that raises "α"**

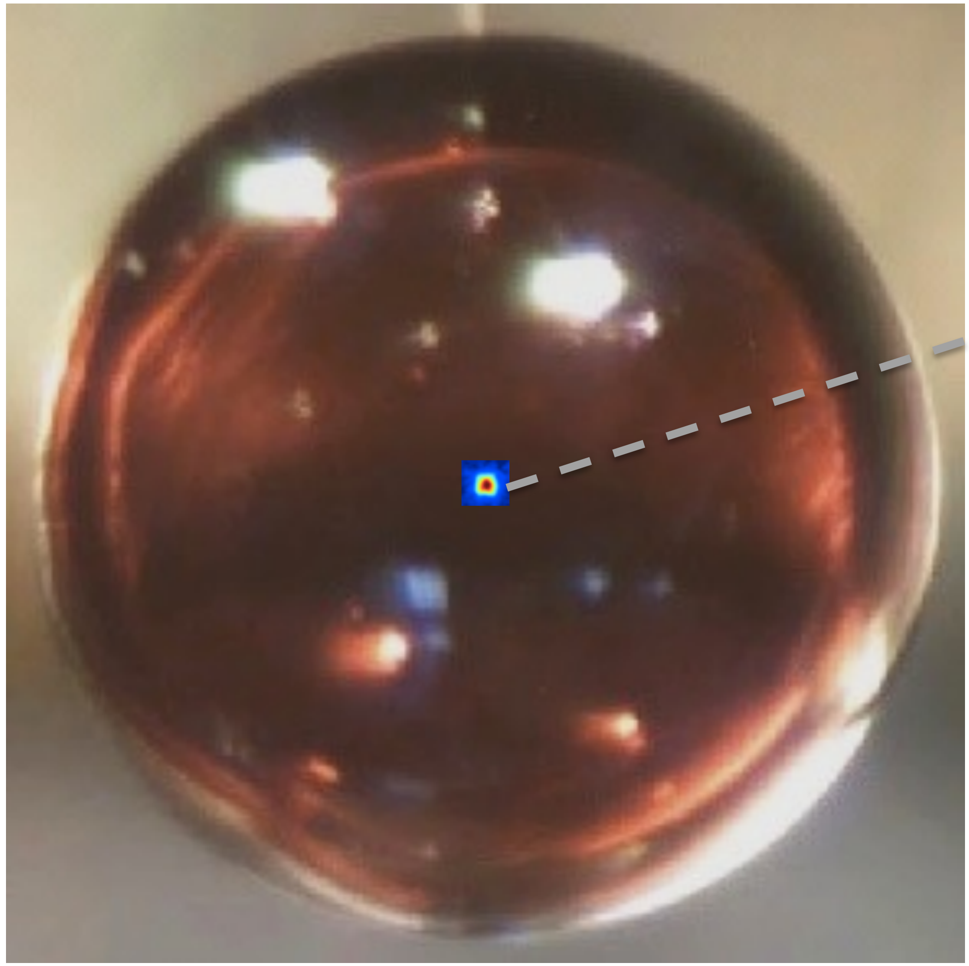
*** Cerjan et al PoP 20, 056319('13)** **** Robey et al PoP 21, 022703('14)**

The Shape Challenge:
Go from here…



~2 mm

… to here, while keeping it round.



~2 mm

…and keep it round ***throughout*** the pulse to eliminate "sloshing"

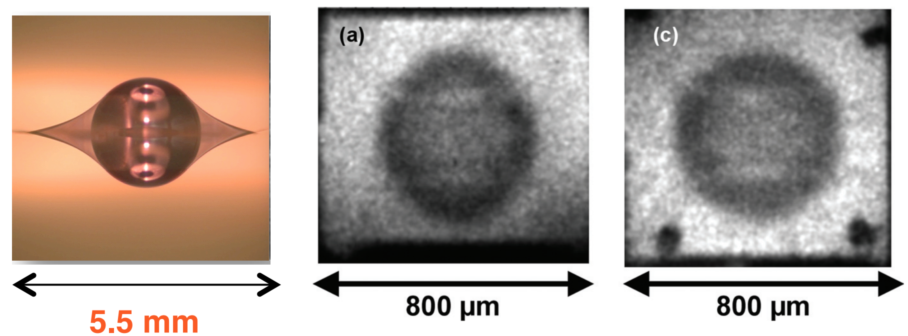
There are multiple sources of asymmetry

- The tent that holds the capsule in place impacts the implosion ~ P4

- Beam pointing and subsequent plasma flow: P2, P4

Backlit shape at r=200 μm:
a) Nominal length hohraum
c) +700 μm hohlraum

R. Town et al PoP 21 , 056313 ('14)



- Cross beam energy transfer varies in time : P2, P4

- Efforts are underway to monitor symmetry throughout the pulse

  - "sloshing" can be a source of asymmetry and residual kinetic energy upon stagnation

Non-uniformities can threaten the implosion in many ways

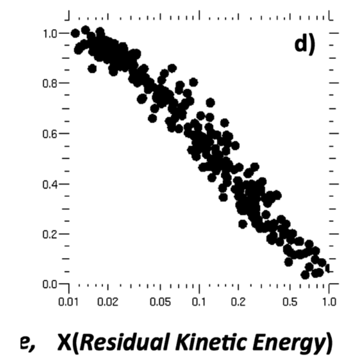
They make compression less efficient.
- **Like squeezing a balloon, gas can bulge out**
- **Less PdV work done on the gas**

If perturbations get too big, the shell can break apart.

If too much cold material gets in, it can cool the forming hot core

Residual kinetic energy means:
less thermal energy in the stagnated assembly.

A. Kricher et al PoP 21, 042708 (2014):

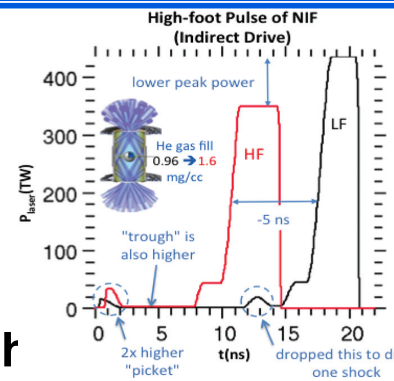


Initial attempts at stagnated core x-radiography:
may indicate “blobs”, not a shell

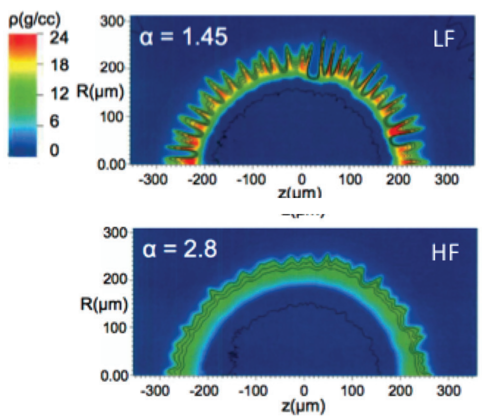
Nuclear diagnostics have supported the notion that the shell is non–uniform, & that bulk velocity elements of the fuel are at play at “stagnation”

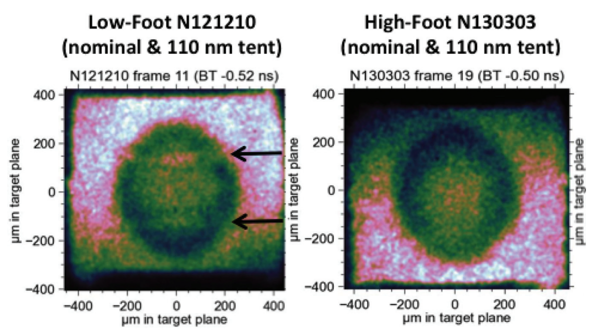
High Foot Implosions are less stressing in many ways, and have given improved performance

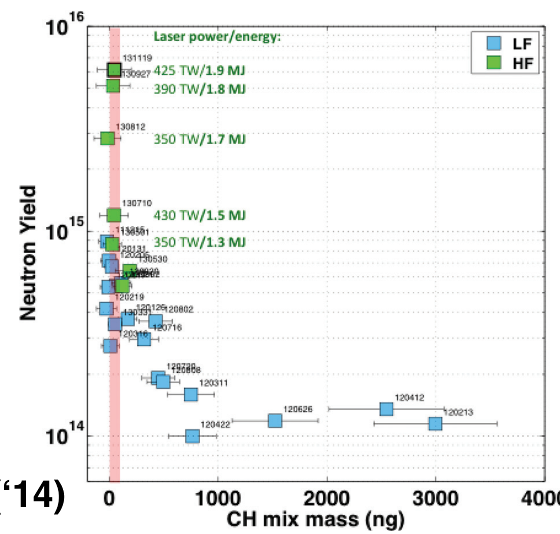
They have higher α, leading to:



- **Lower Convergence ratios**
  - **less sensitivity to symmetry**
- **Lower hydrodynamic instability growtl**
  - **- less of a tent perturbation**
  - **- near zero mix**



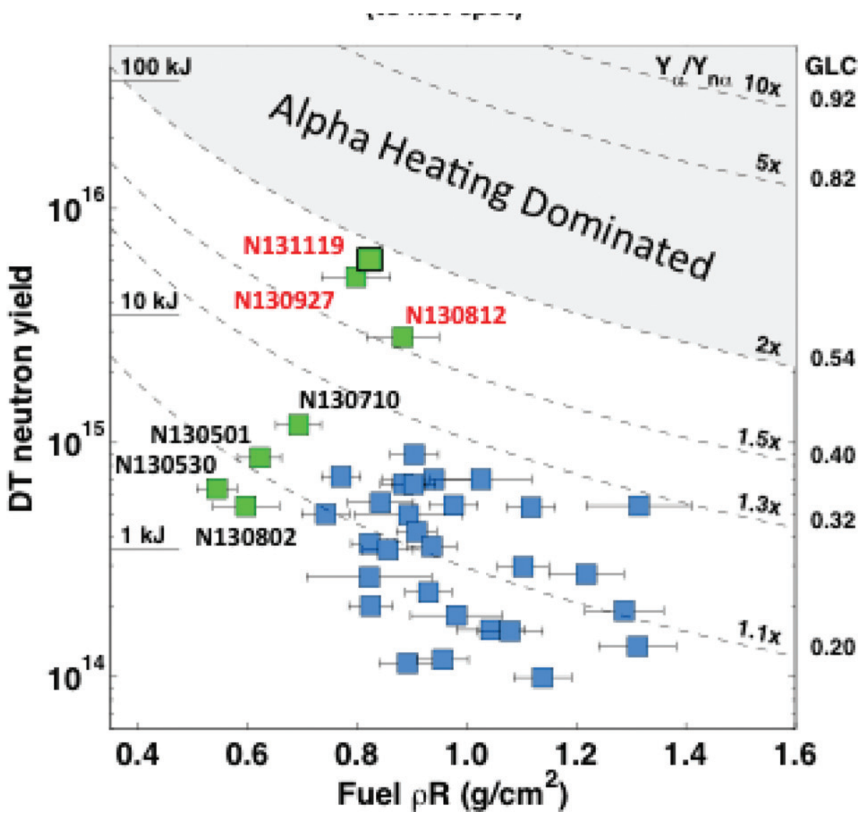




O. Hurricane et al PoP 21, 056314 ('14)

The low amounts of mix imply that samples could be placed in the dense fuel in close proximity to the hot spot fluence

High Foot Implosions have given improved performance over the more stressing Low Foot



O. Hurricane et al PoP 21, 056314 ('14)

Hi-foot Yields are approaching the milestone of 10^{16}, which signifies significant contribution of yield due to alpha heating,

What neutron flux do we expect from a non-igniting but "alpha heating dominant" implosion ?

- $R_f = 30\ \mu m$, & typical $t_0 \sim 100$ psec
- Y = defined as 10^{16} neutrons
- Production rate: 10^{26} neutrons / sec
- Near target center: Fluence is:
  - 10^{24} neutrons / m^2
  - And Flux is:
    - 10^{34} neutrons / m^2 sec

Even an un-ignited NIF capsule is an impressive source of neutrons or NIF nuclear science

Thanks to the entire NIF team!