Status and prospects for burning plasmas via laser fusion

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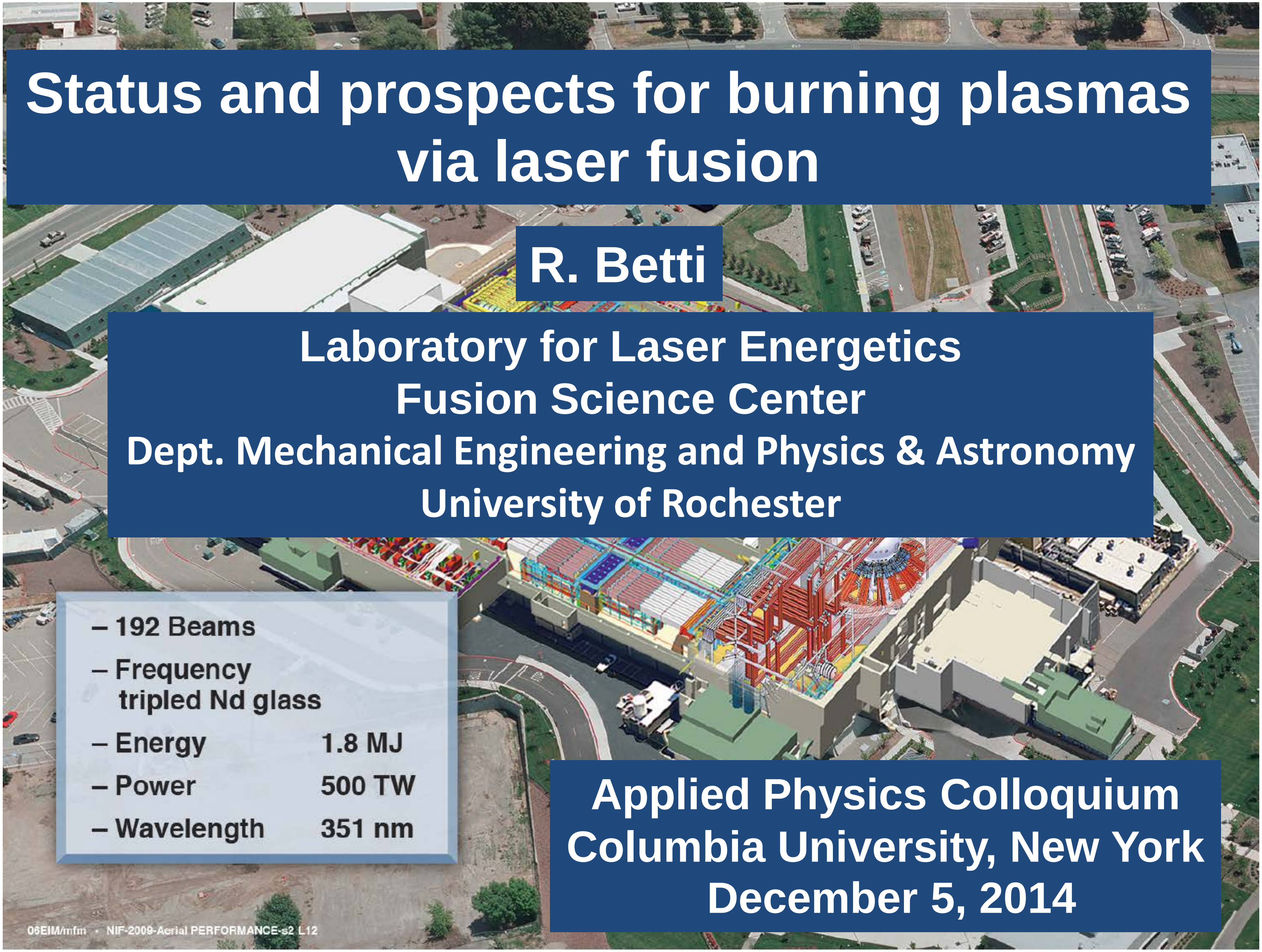


- 192 Beams
- Frequency tripled Nd glass

– Energy	1.8 MJ
– Power	500 TW
– Wavelength	351 nm

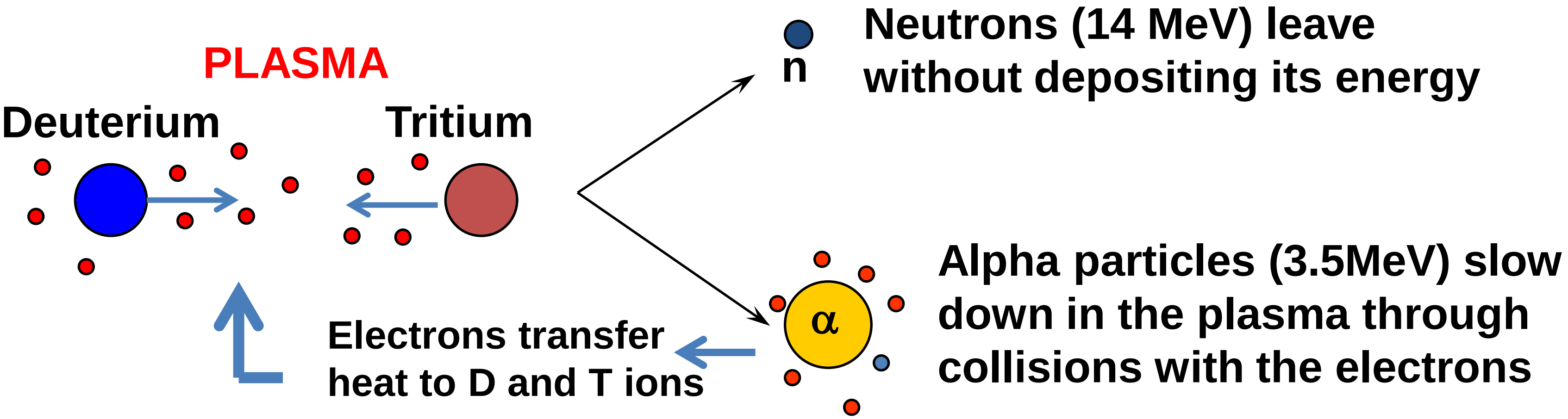
06EIM/mfm • NIF-2009-Aerial PERFORMANCE-s2 L12

Applied Physics Colloquium
Columbia University, New York
December 5, 2014

This talk is about
<u>burning-plasma physics</u> not fusion energy

Alpha particle heating is the mechanism leading to thermonuclear ignition of Deuterium-Tritium fuel

The α-particles release their energy in the plasma thus causing self-heating (or alpha heating).



PLASMA

Deuterium

Tritium

n

Neutrons (14 MeV) leave without depositing its energy

α

Alpha particles (3.5MeV) slow down in the plasma through collisions with the electrons

Electrons transfer heat to D and T ions

Ignition condition

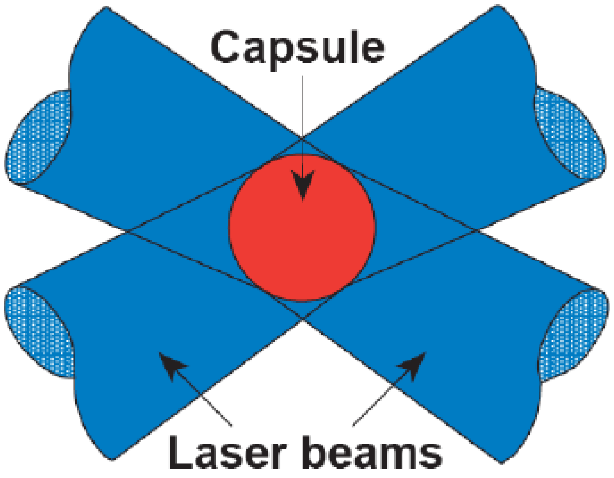
alpha-power> power-losses

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

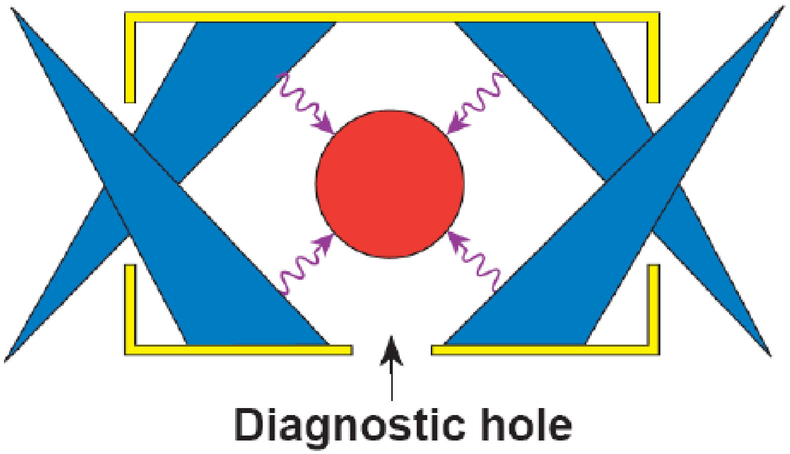
→ Thermonuclear instability → Ignition

The National Ignition Facility (NIF) can explore both indirect- and direct-drive ICF

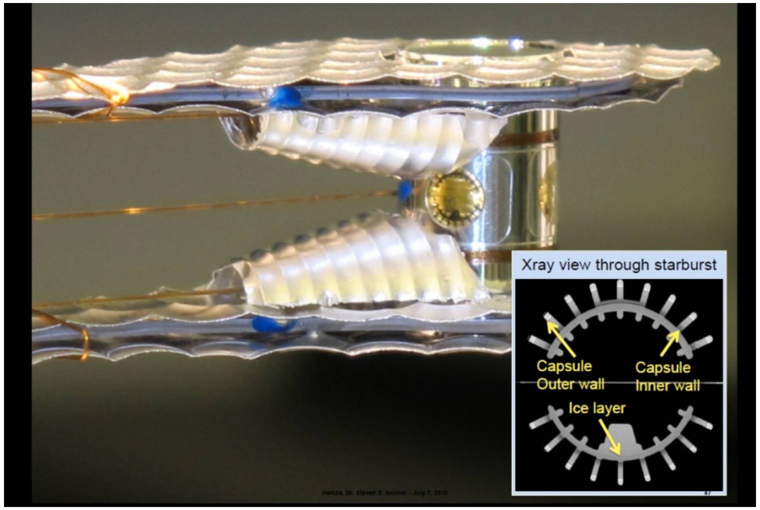
Direct-drive target

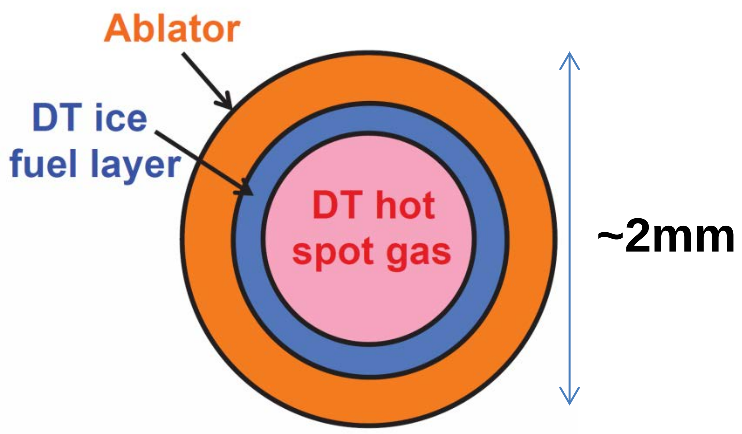


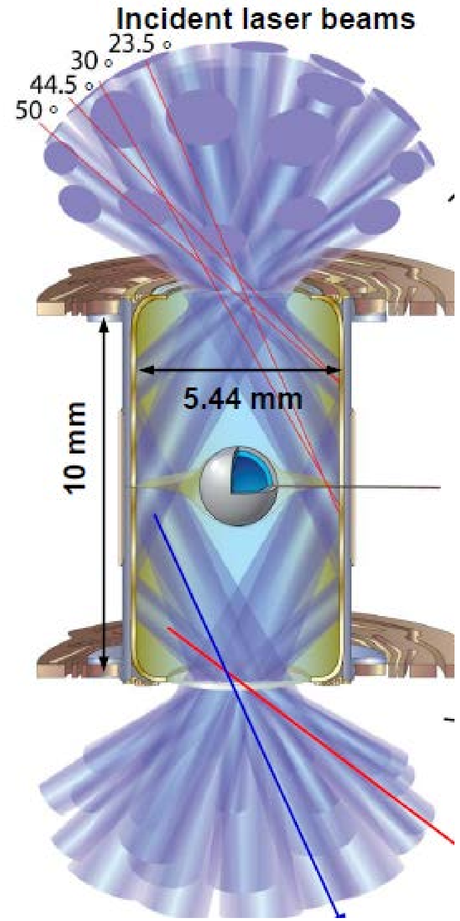
Indirect-drive target



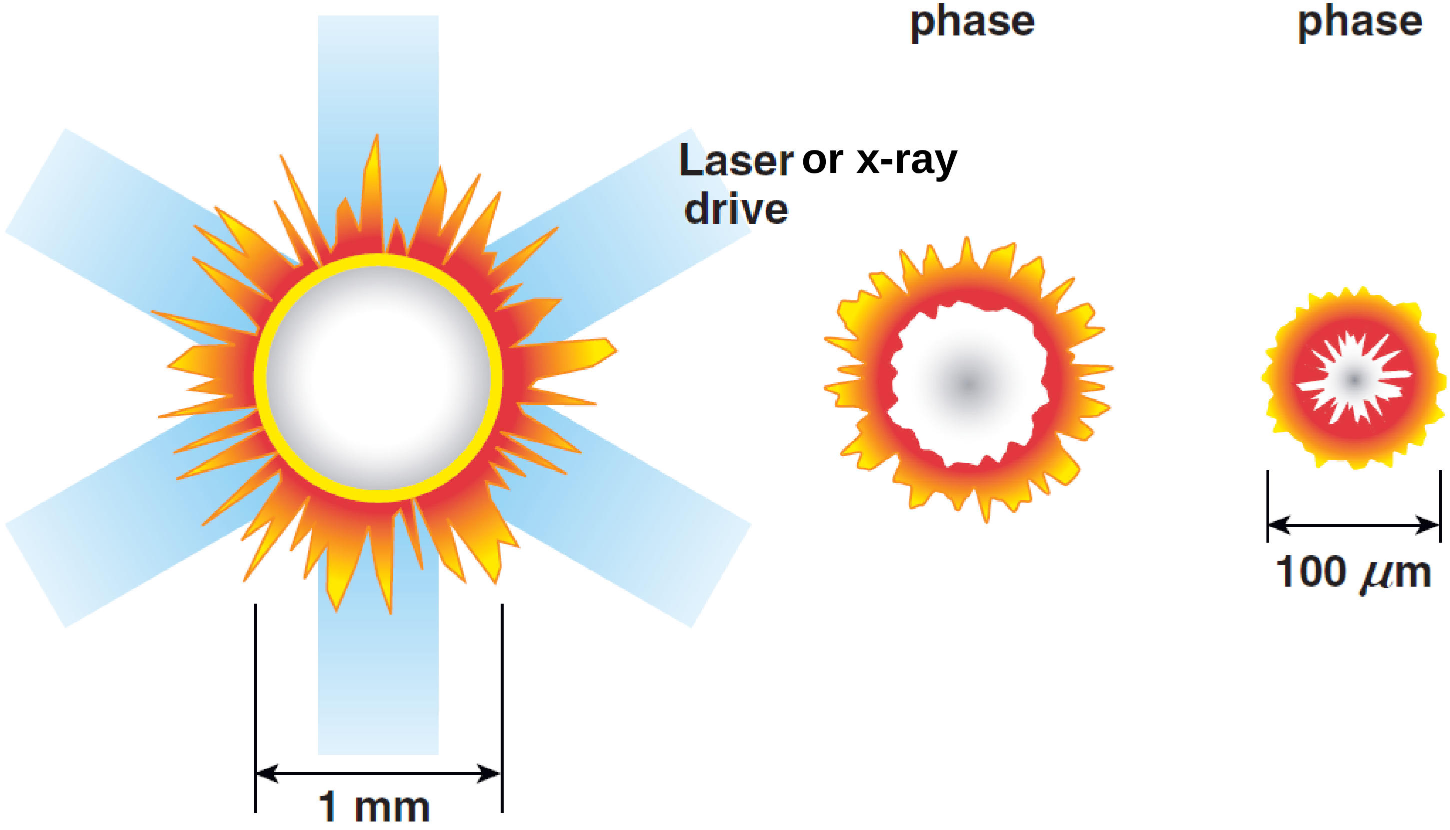
Current ignition experiments on NIF use indirect drive







Implosions are hydrodynamically unstable due to the Rayleigh-Taylor instability



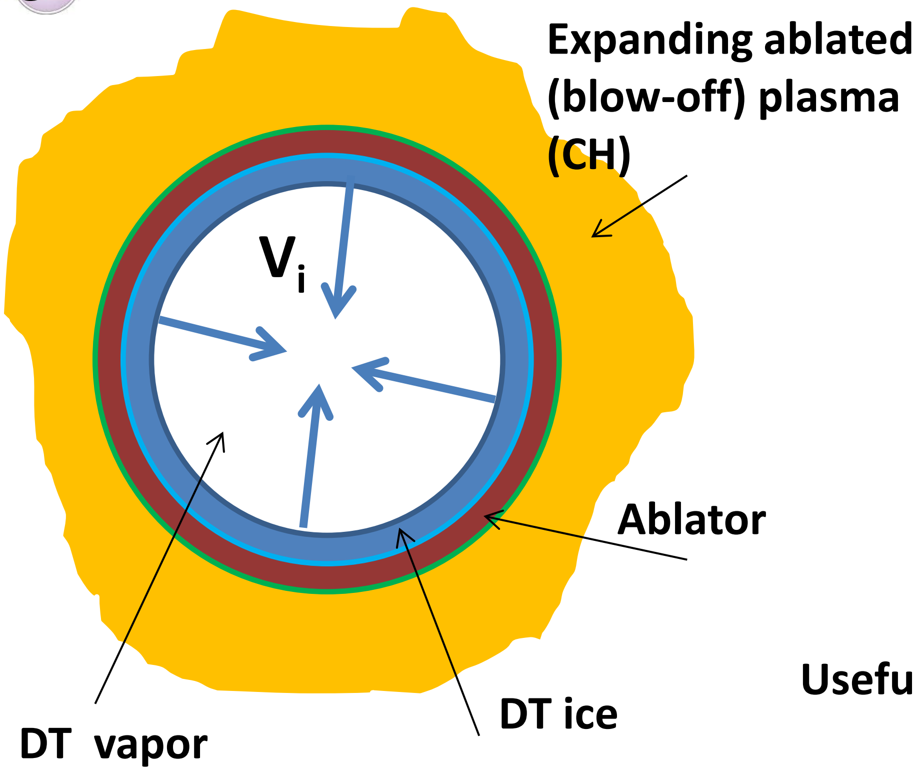
Acceleration phase

Coasting phase

Deceleration phase

Laser or x-ray drive

Driving ICF targets is a very inefficient process



V_i = implosion velocity

Examples:

NIF Indirect Drive
Laser energy = 1.8MJ
Shell final kinetic energy = 14kJ
Total efficiency = 0.8 %

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

Only a small fraction of the driver energy is converted into useful kinetic energy of the implosion

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

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

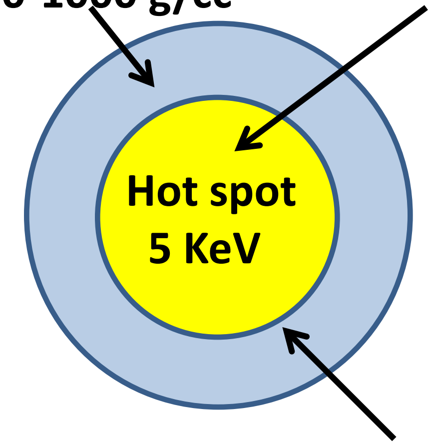
~50% → **Compression and heating of the central hot spot**

~50% → **Compression of the dense shell to provide the “inertial” confinement**

COMPRESSED CORE AT STAGNATION

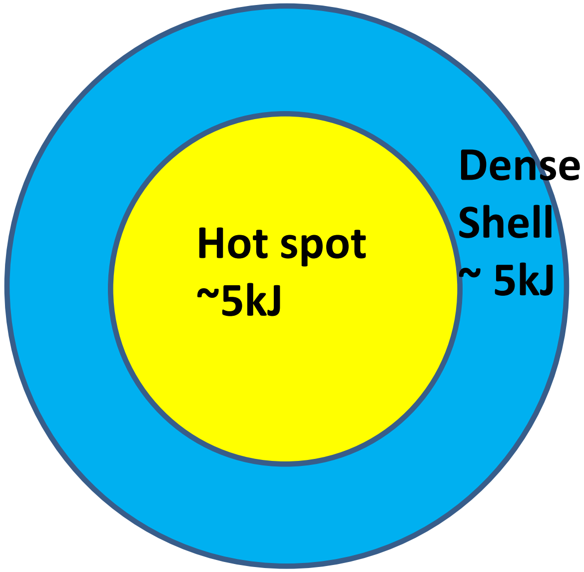
Dense shell
~ 500-1000 g/cc

Ignition takes place in the hot spot

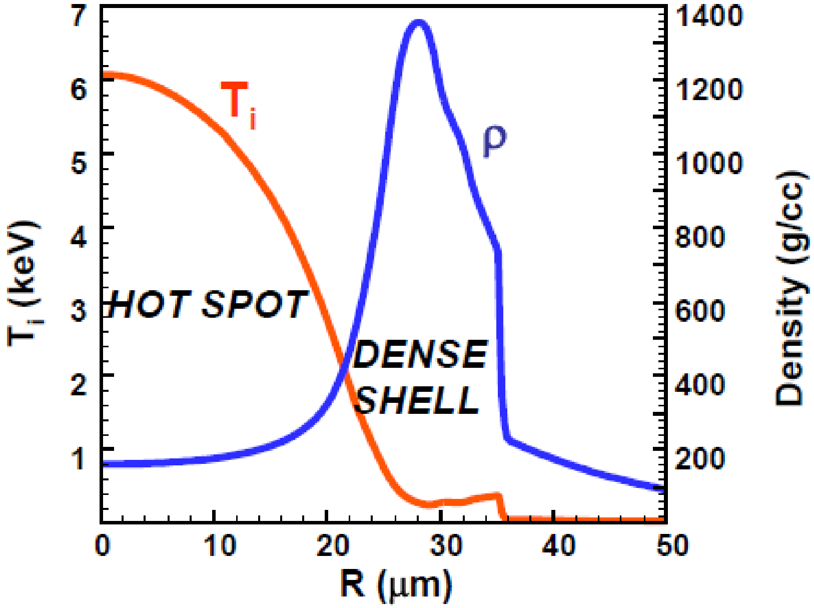


Provides the confinement of the hot spot and a large supply of thermonuclear fuel

Up to the onset of ignition, burning plasmas are confined within the "hot spot"



Stagnation density and temperature



The energy balance determines the time evolution of the plasma pressure

Fusion
Plasma
(HOT SPOT)
$P_{no\alpha}$

- **The DT plasma is brought to a pressure $P_{no\alpha}$ by a spherical piston (the imploding shell)**
- **The alpha particles deposit their energy in the plasma while the plasma looses energy on a time scale τ**

ENERGY BALANCE

Fusion reactivity

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

3.5 MeV

$$P\approx 2nT$$

Confinement time

The dimensionless form of the energy balance only depends on the no-alpha Lawson[1] parameter

$$\frac{dP}{dt}=\frac{P}{\tau}\left[\frac{P\tau}{S_\alpha(T)}-1\right] \qquad S_\alpha(T)\equiv\frac{24T^2}{\varepsilon_\alpha\langle\sigma v\rangle}$$

- **Dimensionless variables and assume** $\langle\sigma v\rangle\sim T^2 \rightarrow S_\alpha(T)=S_\alpha=const$

$$\frac{d\hat{P}}{d\hat{t}}=\hat{P}\left[\chi_{no\alpha}\hat{P}-1\right] \qquad \hat{P}\equiv\frac{P}{P_{no\alpha}} \qquad \hat{t}\equiv\frac{t}{\tau} \qquad \hat{P}(0)\equiv 1$$

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

← **No-alpha Lawson parameter**

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

[1] Lawson, Proc. Phys. Soc. London (1957)

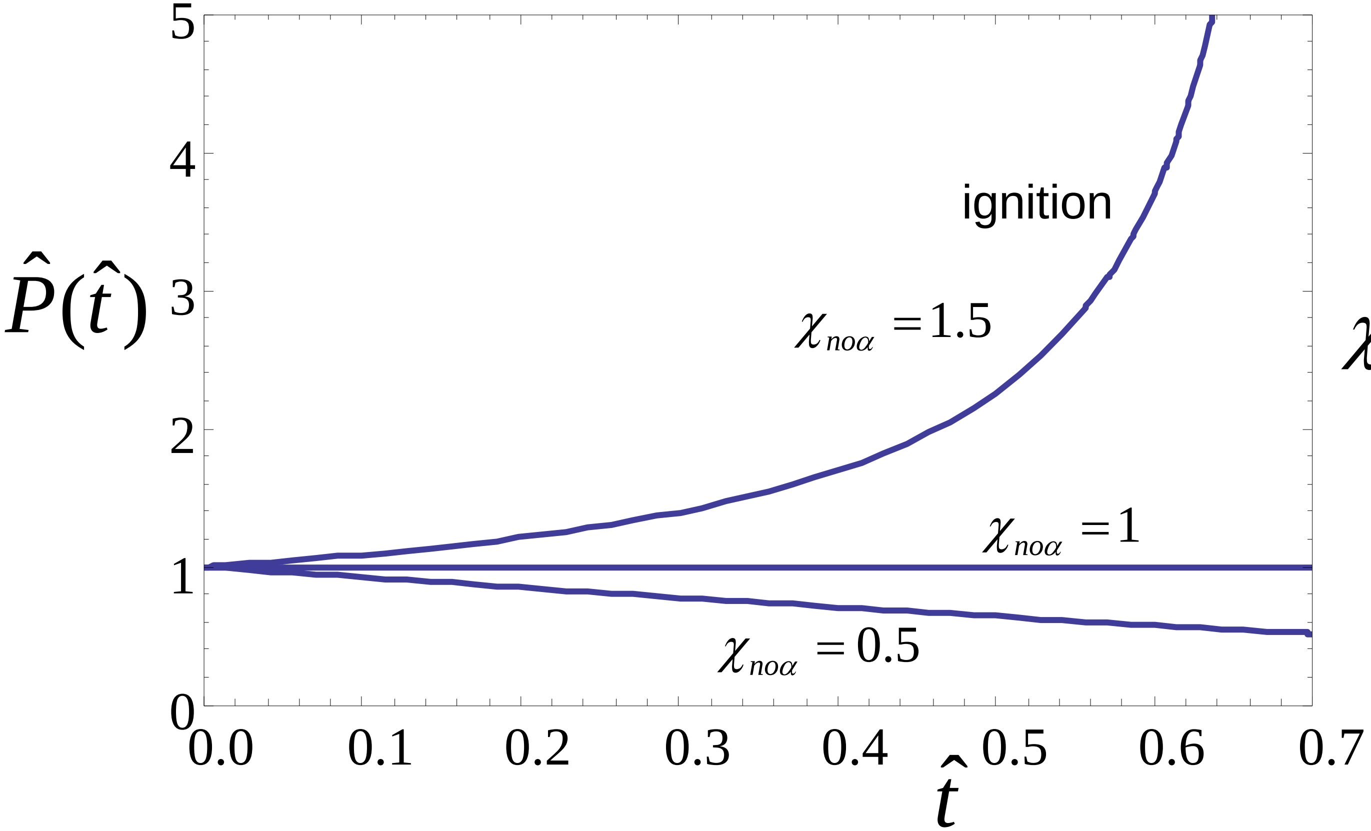
The explosive solution defines the ignition condition determined by the no-alpha Lawson parameter

$$\hat{P} = \frac{1}{\chi_{no\alpha} - (\chi_{no\alpha} - 1)e^{\hat{t}}}$$

IGNITION CONDITION

$$\chi_{no\alpha} \geq 1$$

$$P_{no\alpha}\tau = S_\alpha \Rightarrow \left[P_{no\alpha}\tau\right]_{ign}^{\min}$$



$$\chi_{no\alpha} \equiv \frac{P_{no\alpha}\tau}{\left[\underset{S_\alpha}{P_{no\alpha}\tau}\right]_{ign}^{\min}}$$

A neutron yield with alphas and a yield without alphas can be defined

- **Neutron yield including alpha particle heating for subignited plasmas**

P^2

$$Yield_\alpha \sim V\tau P_{no\alpha}^2 \int_0^\infty \hat{P}^2 d\hat{t} = \frac{V\tau P_{no\alpha}^2}{\chi_{no\alpha}^2}\left[Ln\left(\frac{1}{1-\chi_{no\alpha}}\right) - \chi_{no\alpha}\right]$$

Yield$_\alpha$ is measured in the experiments

- **Neutron yield if alpha particle heating is switched off**

$$\frac{d\hat{P}}{d\hat{t}} = \hat{P}\left[\cancel{\chi_{no\alpha}\hat{P}} - 1\right] \qquad \hat{P} = \exp\left(-\hat{t}\right)$$

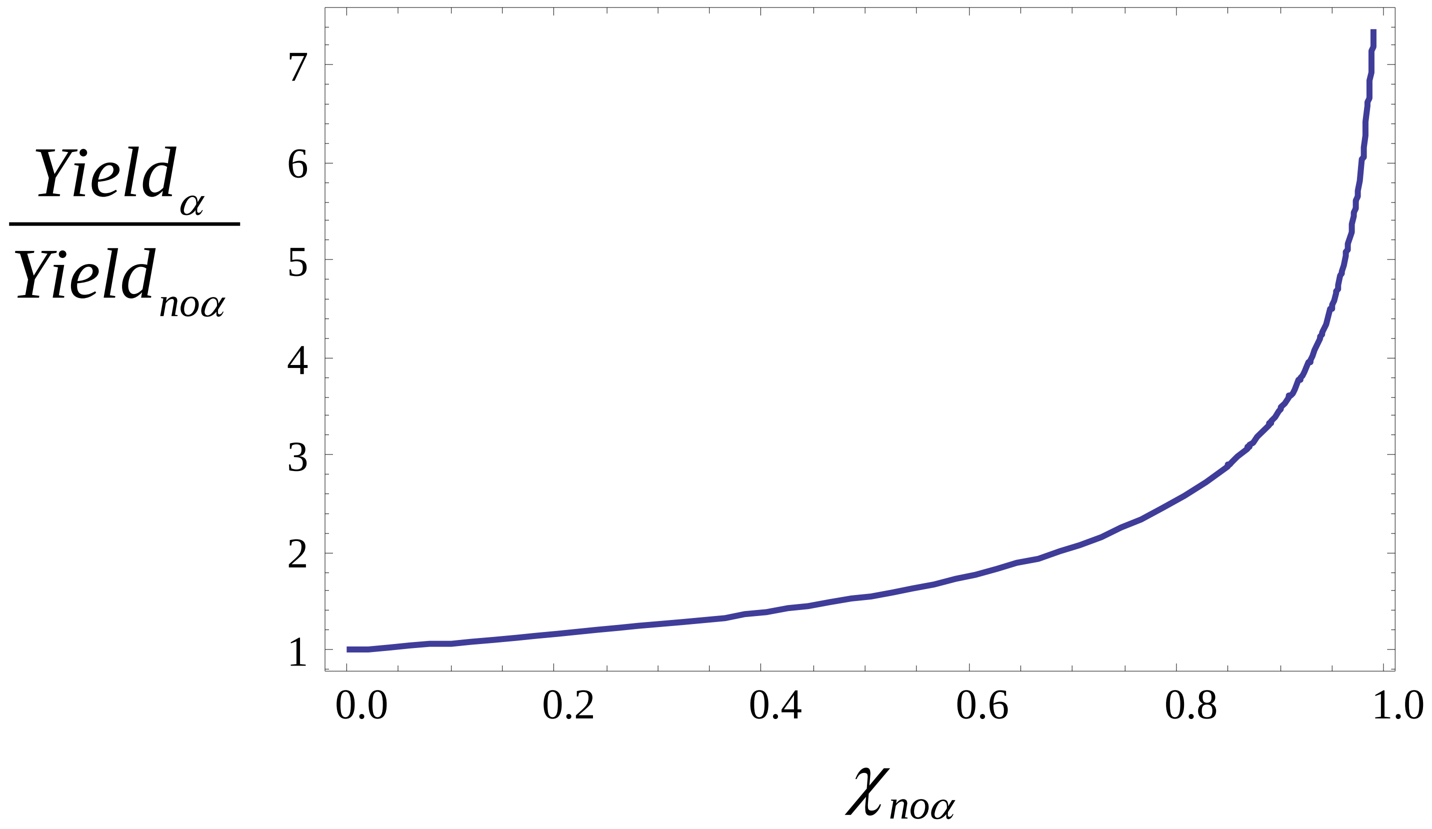
$$Yield_{no\alpha} \sim V\tau P_{no\alpha}^2 \int_0^\infty \hat{P}^2 d\hat{t} = \frac{V\tau P_{no\alpha}^2}{2}$$

Yield$_{no\alpha}$ cannot be measured in DT experiments

The amplification of the yield due to alpha heating is a unique function of the no-alpha Lawson parameter

$$\frac{Yield_{\alpha}}{Yield_{no\alpha}} = \frac{2}{\chi_{no\alpha}^{2}}\left[Ln\left(\frac{1}{1-\chi_{no\alpha}}\right)-\chi_{no\alpha}\right]$$

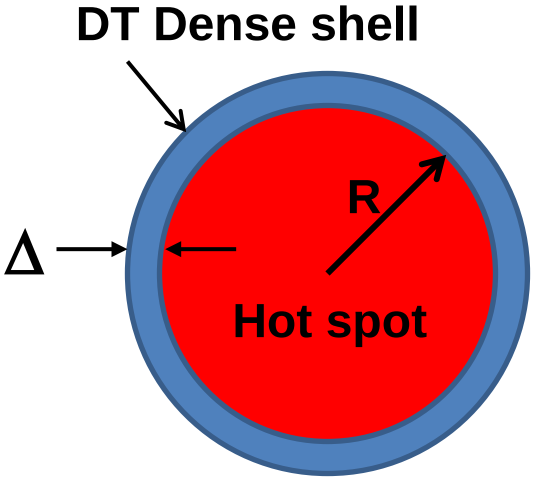
$$\chi_{no\alpha} \equiv \frac{P_{no\alpha}\tau}{\left[P_{no\alpha}\tau\right]_{ign}^{\min}}$$



How can one measure the no-alpha Lawson parameter? Start from estimating the confinement time τ

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

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



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

Shell mass

Areal density

$$M_{DT}^{sh} \sim \left(\rho_{shell}\Delta\right)R^2 \qquad V \sim R^3$$

A simple formula relates the Lawson parameters with and without alphas (using previous slide)

$$Yield \sim P^2 \tau V$$

$$\chi \equiv \frac{P\tau}{S_\alpha} = \frac{P\tau}{\left[P\tau\right]^{ig}_{\min}}$$

$$\boxed{\chi^3 \sim \frac{Yield}{M^{sh}_{DT}} \left(\rho\Delta\right)^2}$$

- $Yield_\alpha$ is measured
- Areal density $\rho\Delta$ is measured
- Mass of shell is known

$$\chi_{no\alpha} \sim Yield^{1/3}_{no\alpha}$$

$$\chi_\alpha \sim Yield^{1/3}_\alpha$$

$$\boxed{\chi_\alpha = \chi_{no\alpha} \left(\frac{Yield_\alpha}{Yield_{n\alpha}}\right)^{1/3}}$$

χ_α can be measured

The amplification of the yield due to alpha heating is also a unique function of the Lawson parameter with alphas

$$\frac{Yield_{\alpha}}{Yield_{no\alpha}} = \frac{2}{\chi_{no\alpha}^{2}}\left[Ln\left(\frac{1}{1-\chi_{no\alpha}}\right)-\chi_{no\alpha}\right]$$

$$\chi_{\alpha} = \chi_{no\alpha}\left(\frac{Yield_{\alpha}}{Yield_{n\alpha}}\right)^{1/3}$$

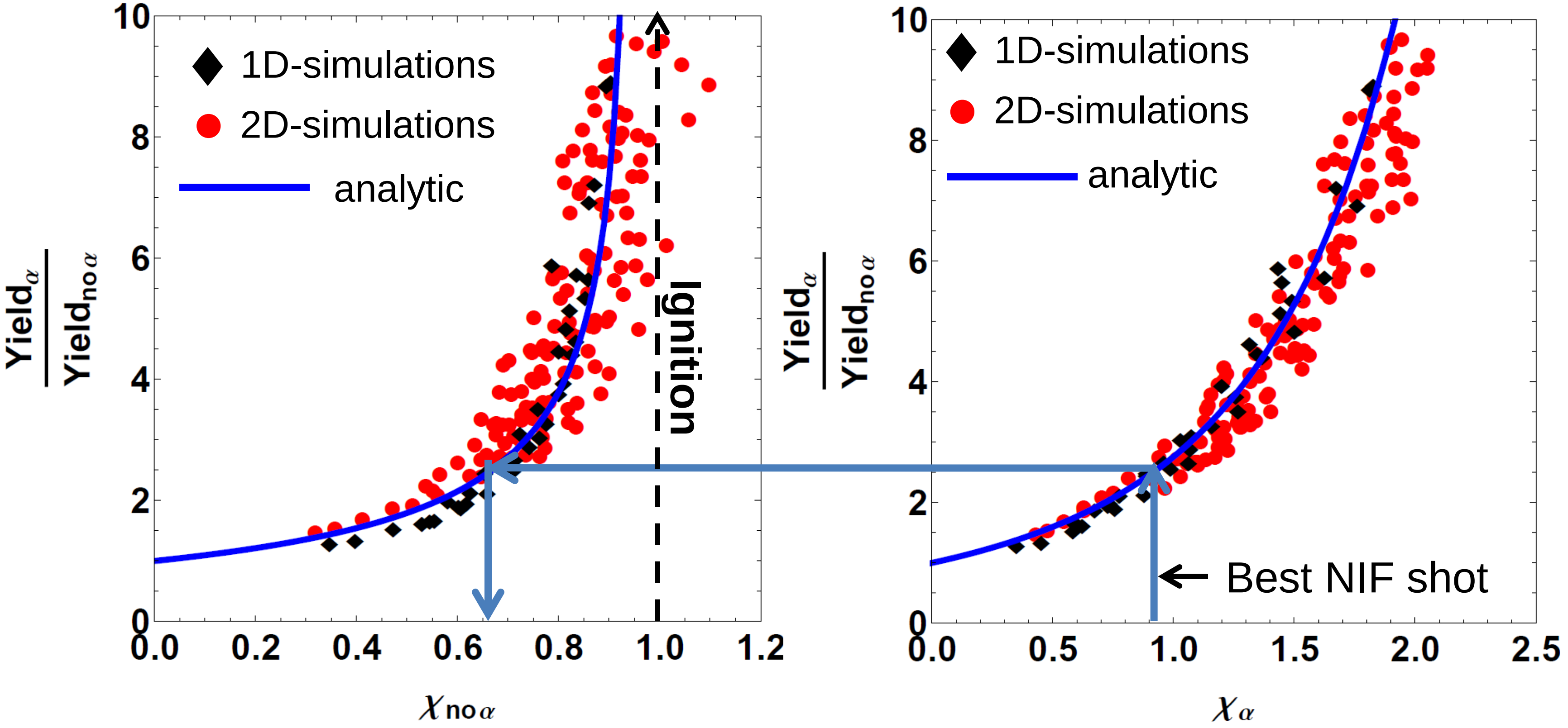
Yield amplification →

$$\frac{Yield_{\alpha}}{Yield_{n\alpha}} = F\left(\chi_{\alpha}\right)$$

$$\chi_{\alpha} \sim \left(\frac{0.24Yield_{16}^{\alpha}}{M_{DT(mg)}^{sh}}\right)^{1/3}\left(\rho R_{g/cm^{2}}\right)^{2/3}$$

← χ_α can be measured

In the best NIF shot the fusion yield increased by about 2.5x due to alpha heating



$$\boxed{\chi_{no\alpha} \equiv \frac{[P\tau]_{no\alpha}}{[P\tau]^{ign}_{no\alpha}}}$$

Best High-Foot NIF shot:
ρR ≈ 0.7g/cm², Yield = 10^{16}, M_{DT} = 0.17mg

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

A significant amount of alpha particle energy (relative to the pdV work) was obtained in NIF shot N140120

$$\langle \mathrm{P} \rangle \approx 180 Gbar$$

$$\langle \mathrm{T} \rangle \approx 5 keV$$

$$\mathrm{R}_{hot-spot} \approx 34 \mu m$$

$$E_{hot-spot} \approx 5 kJ$$

$$E_{rad}^{tot} \approx 2.3 kJ$$

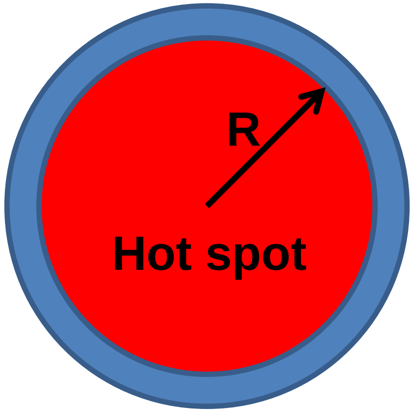
$$E_{\alpha}^{dep} \approx 3.8 kJ$$

$$E_{fusion} \approx 26 kJ$$

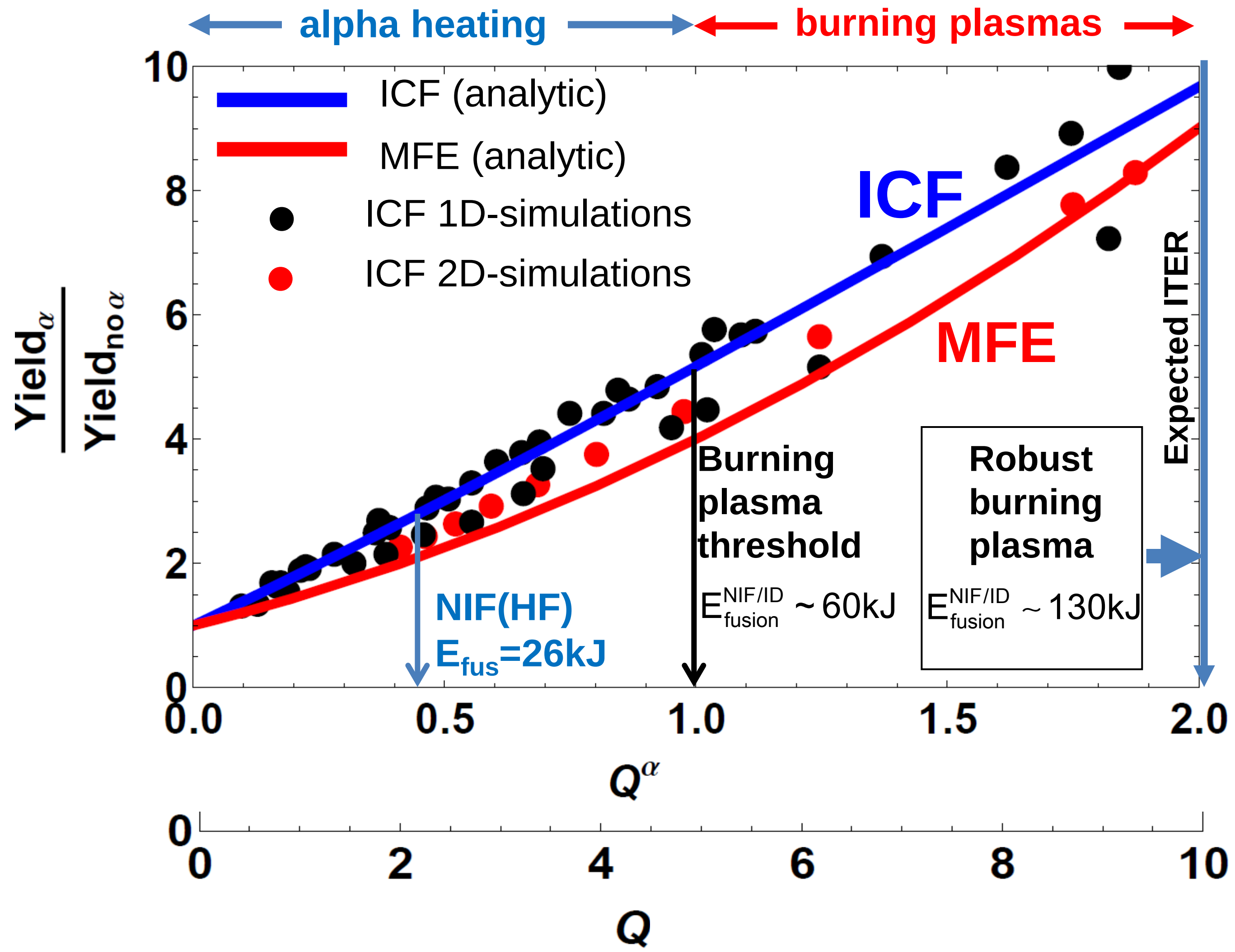
$$E_{pdV}^{input} \approx 4.1 kJ$$

$$Q_{hot-spot}^{\alpha} = \frac{0.5 E_{\alpha}^{dep}}{E_{pdV}^{input}} \approx 0.45$$

$$Q_{hot-spot}^{fusion} = 5 Q_{hot-spot}^{\alpha} \approx 2.2$$



The alpha heating contribution can be compared between ICF and MFE (only physics here, no energy)



$$Q^\alpha = \frac{E_\alpha}{E^{input}}$$

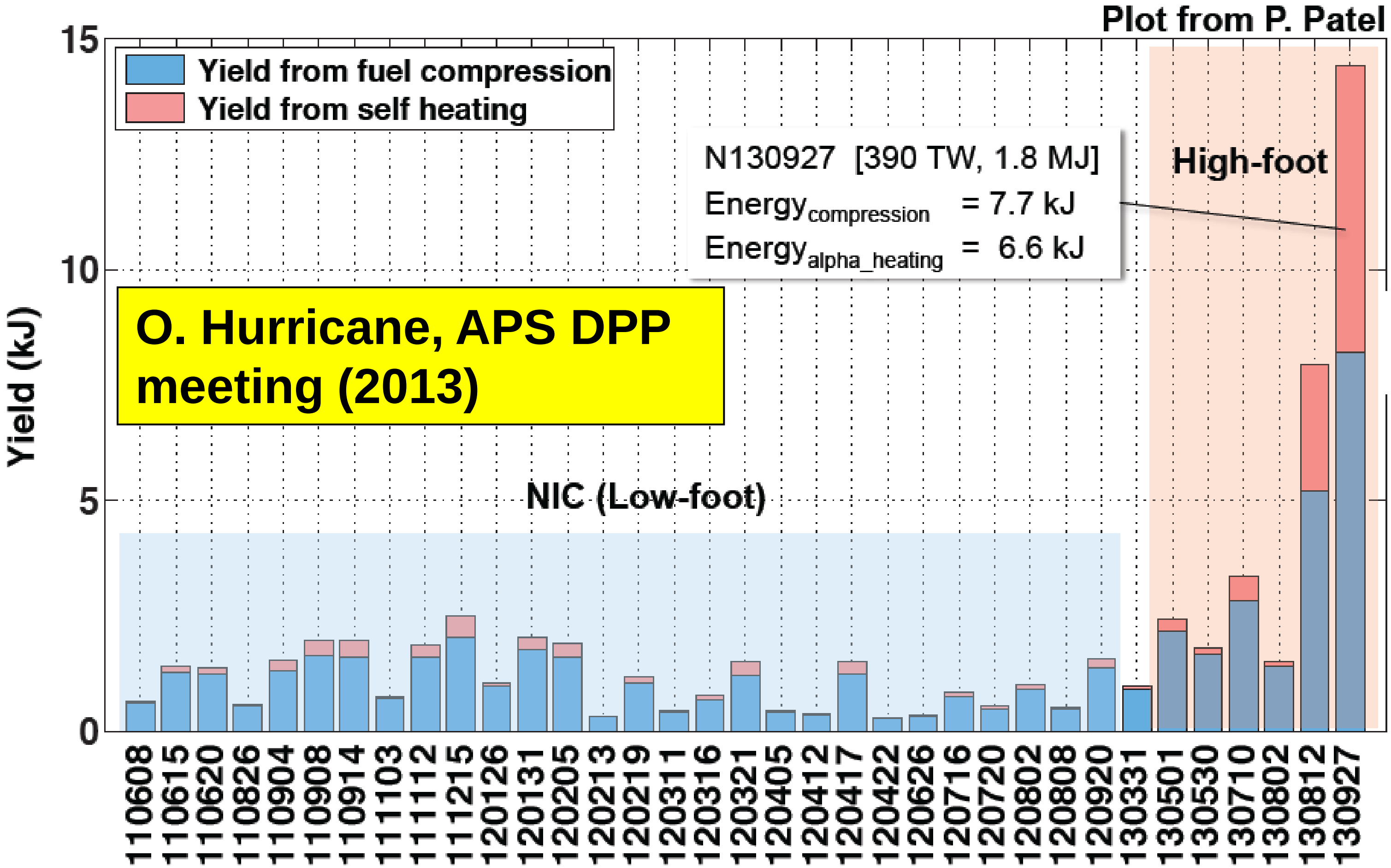
$$Q = \frac{E_{fusion}}{E^{input}}$$

How was the alpha heating result achieved by O. Hurricane and his team at LLNL?

Hurricane et al, Nature, March 2014
Parks et al, Phys. Rev. Lett. 2014

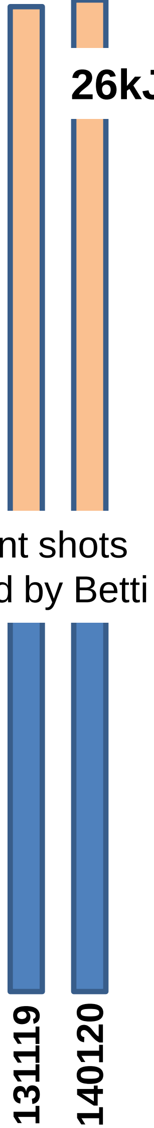
We finally have an implosion where a large fraction of the total fusion output is from α-particle self-heating

Plot from P. Patel



N130927 [390 TW, 1.8 MJ]
$\text{Energy}_{\text{compression}}$ = 7.7 kJ
$\text{Energy}_{\text{alpha\_heating}}$ = 6.6 kJ

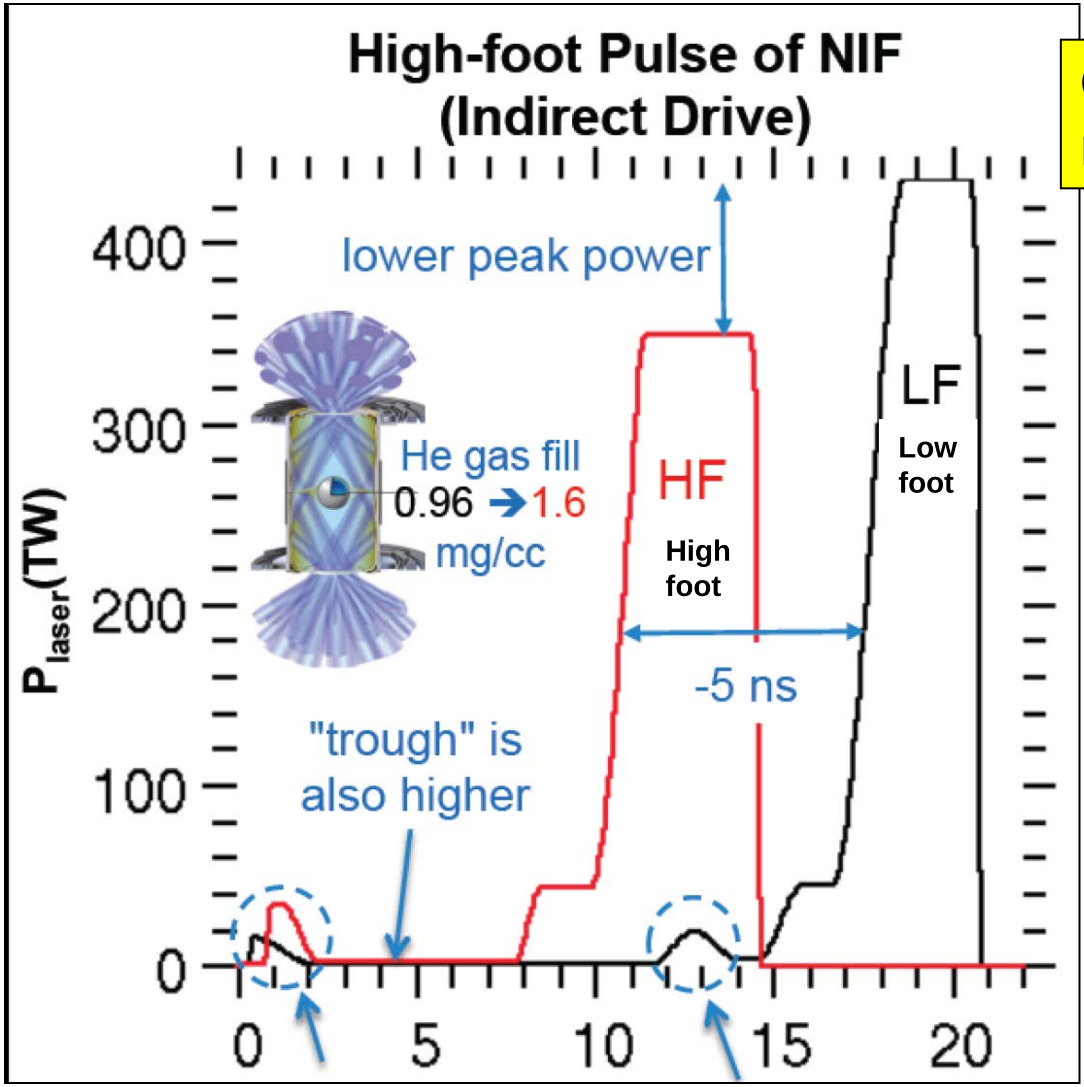
O. Hurricane, APS DPP meeting (2013)



Recent shots added by Betti

Joint WCI/NIF Team:
D. Callahan, E. Dewald, T. Dittrich,T. Doeppner, D. Hinkel, L. Berzak Hopkins, O. Hurricane, P. Kervin, J. Lee Kline (LANL), S. LePape, T. Ma, J. Milovich, J. Moody, A. Pak, H.-S. Park, B. Remington, H. Robey, J. Salmonson, NIF operations, NIF cryo, NIF targets, GA, LLE, & M.I.T.

The best NIF implosions used the High-Foot laser pulse that drives stronger shocks in the “foot”



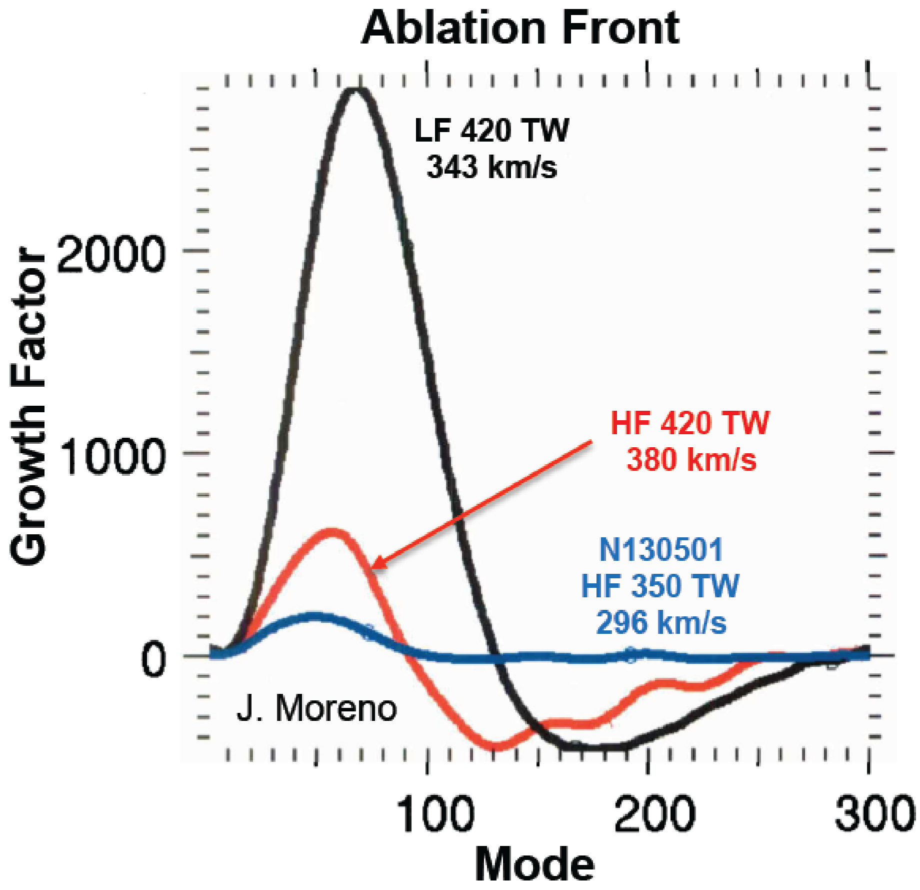
O. Hurricane, APS DPP meeting

The high foot pulse set the imploding shell on a higher isentrope α (nothing to do with alpha particles**) because it launches stronger shocks in the “foot” of the pulse when the shell density is low**

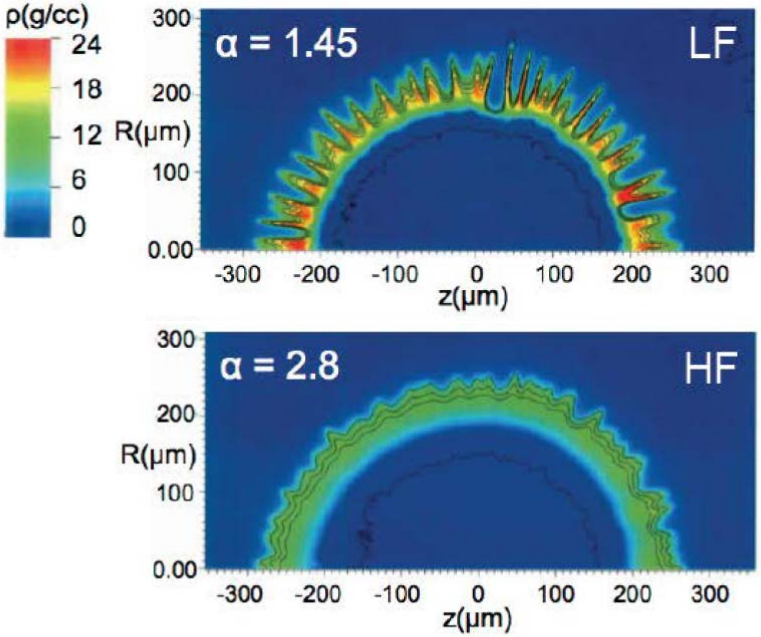
Stronger picket

Drop this precompession

High-foot growth-factor calculations and simulations are consistent with the expectation of less instability



O. Hurricane, APS DPP meeting



Instability growth rate:
e.g. Bodner (1974),
Betti, et. al. (1998)

$$\gamma = \alpha_2(Fr,\upsilon)\sqrt{\frac{kAg}{1+kL_\rho}} - \beta_2(Fr,\upsilon)kv_a$$

$\sim T^{2.5}$ "Foot"

increases with α "Adiabat"

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

$$\chi_{\text{no}\alpha} \sim E_{\text{kin}}^{0.37}\,\text{YOC}^{0.4}\,\frac{V_{imp}^{2}}{\alpha_{F}^{3/5}}$$

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

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

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

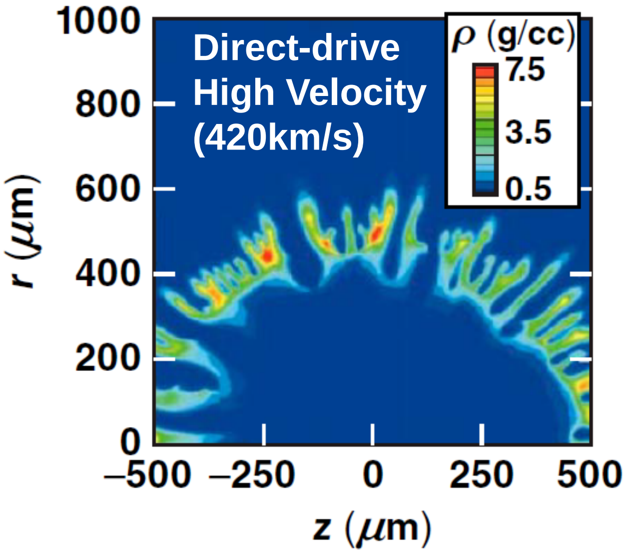
E_{kin} = kinetic energy

YOC = Yield-Over-Clean = Yield(3D)/Yield(1D)

YOC is $\geq$ 50% in NIF High Foot

V_{imp} = Implosion Velocity

α_F = Adiabat (entropy)



Easiest options to approach ignition: Increase V_{imp} and/or reduce the Adiabat (this is the current path of the HF campaign) but stability may eventually become an issue again (YOC drops)

The current path to indirect drive ignition includes: Higher velocity, mitigating the Rayleigh-Taylor instability, trying new ablators and new hohlraums

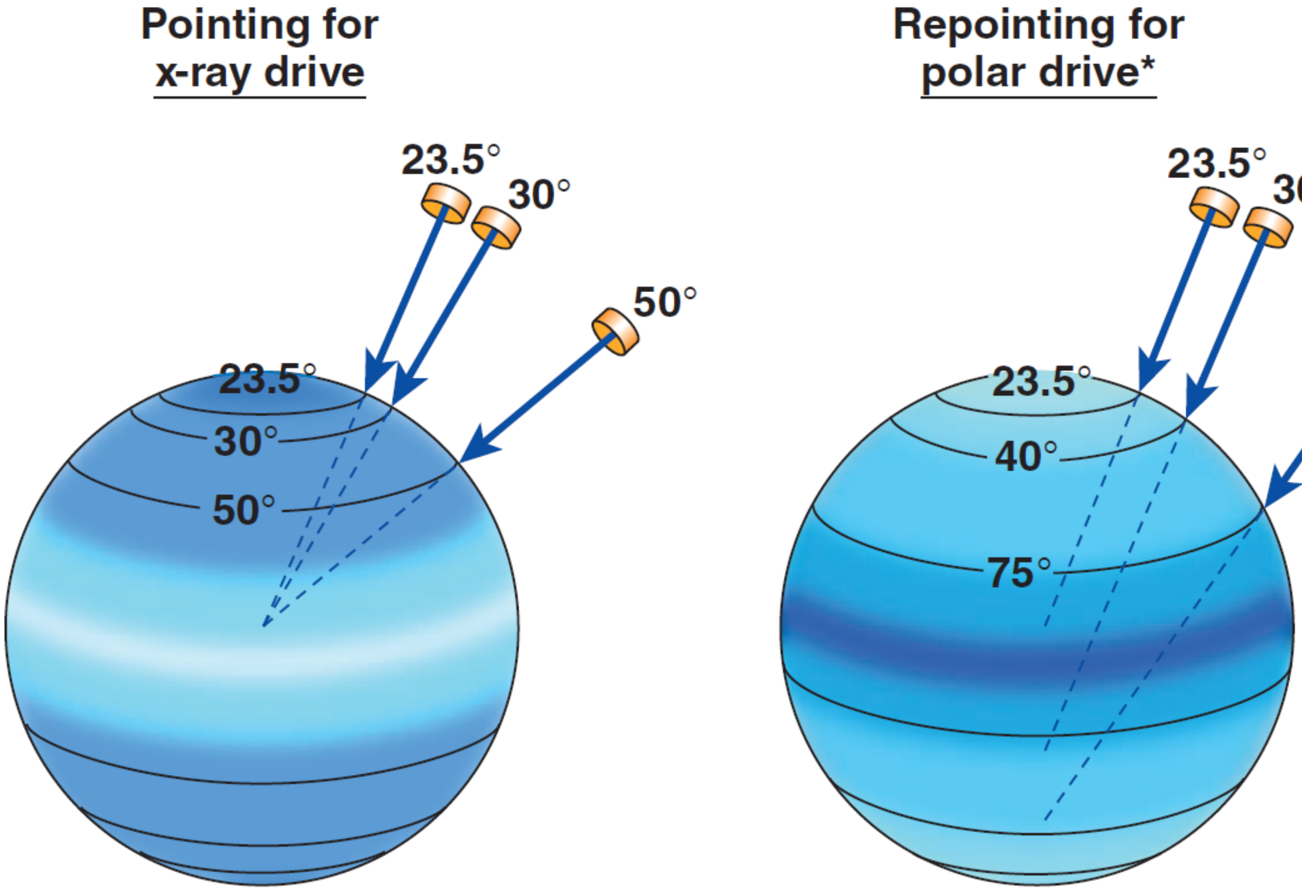
Near Vacuum Hohlraums have the potential of eliminating the Laser-Plasma-Instabilities problem leading to better control of the implosion symmetry and greater x-ray energy

HDC (diamond) Ablator has higher density and requires shorter laser pulses allowing the use of vacuum hohlraums (with less energy losses due to laser-plasma instabilities)

Beryllium Ablator has greater hydrodynamic efficiency allowing a more massive (and more stable) shell to be imploded

Direct-Drive Laser Fusion

Ignition attempts using direct drive require repointing the NIF beams (polar direct drive)



Pointing for x-ray drive

Repointing for polar drive*

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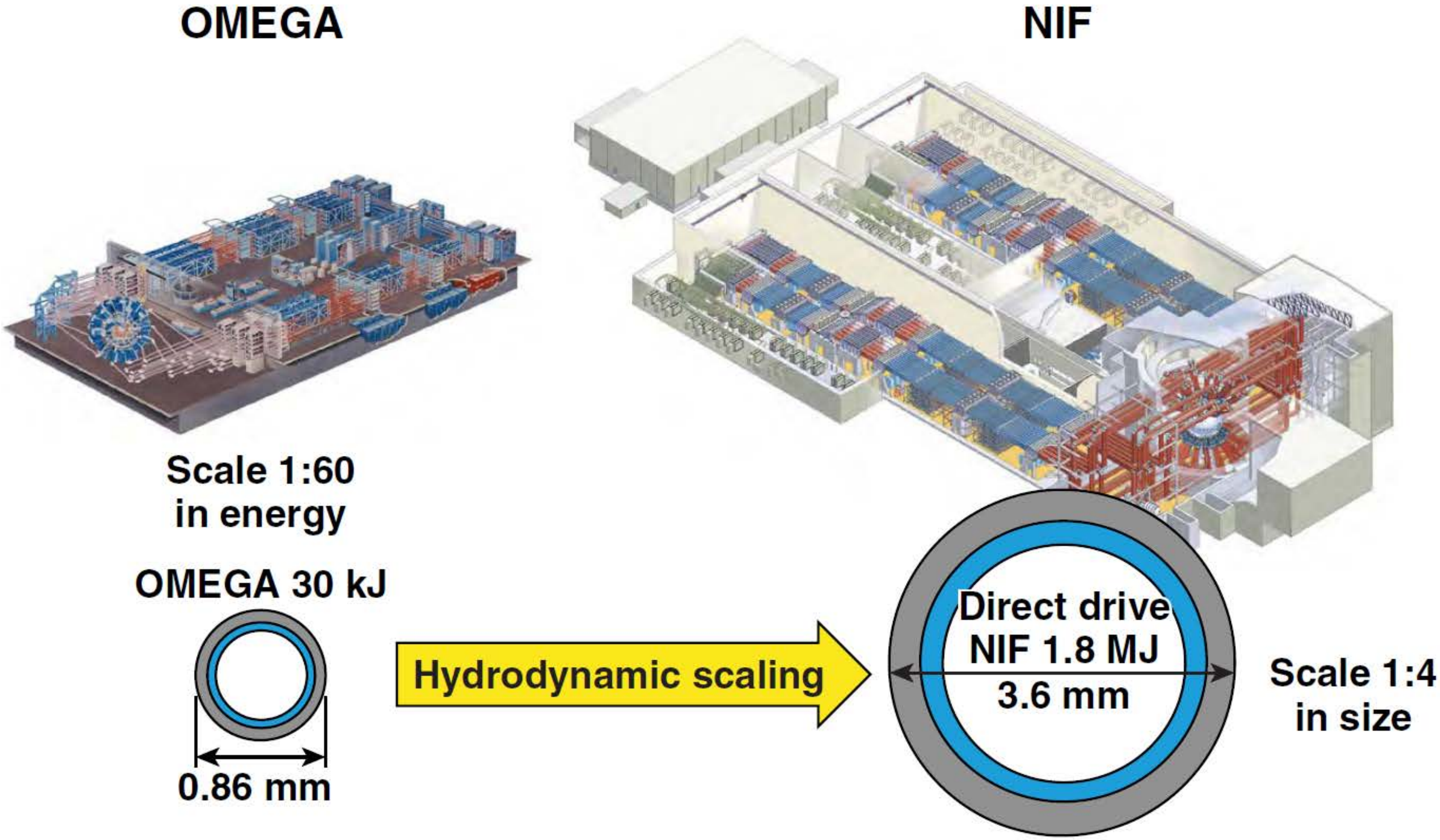
*S. Skupsky *et al.*, Phys. Plasmas 11, 2763 (2004).

Initial experiments are in progress to test direct-drive on NIF

Hydrodynamic equivalence provides a tool to scale the performance of OMEGA implosions to NIF energies



OMEGA

NIF

Scale 1:60
in energy

OMEGA 30 kJ

0.86 mm

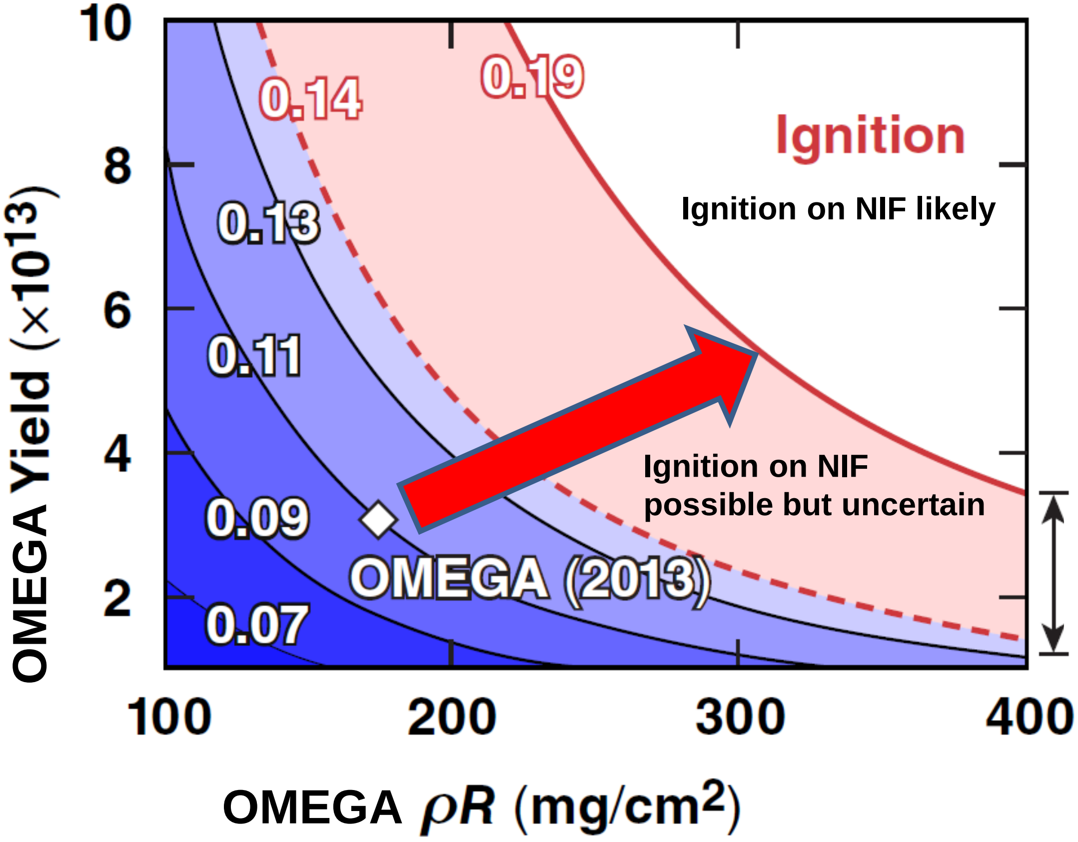
Hydrodynamic scaling

Direct drive
NIF 1.8 MJ
3.6 mm

Scale 1:4
in size

Hydro-equivalent scaled-down experiments are carried out on OMEGA

OMEGA implosions continue to improve towards the goal of demonstrating hydro-equivalent ignition at 1.5MJ of laser energy

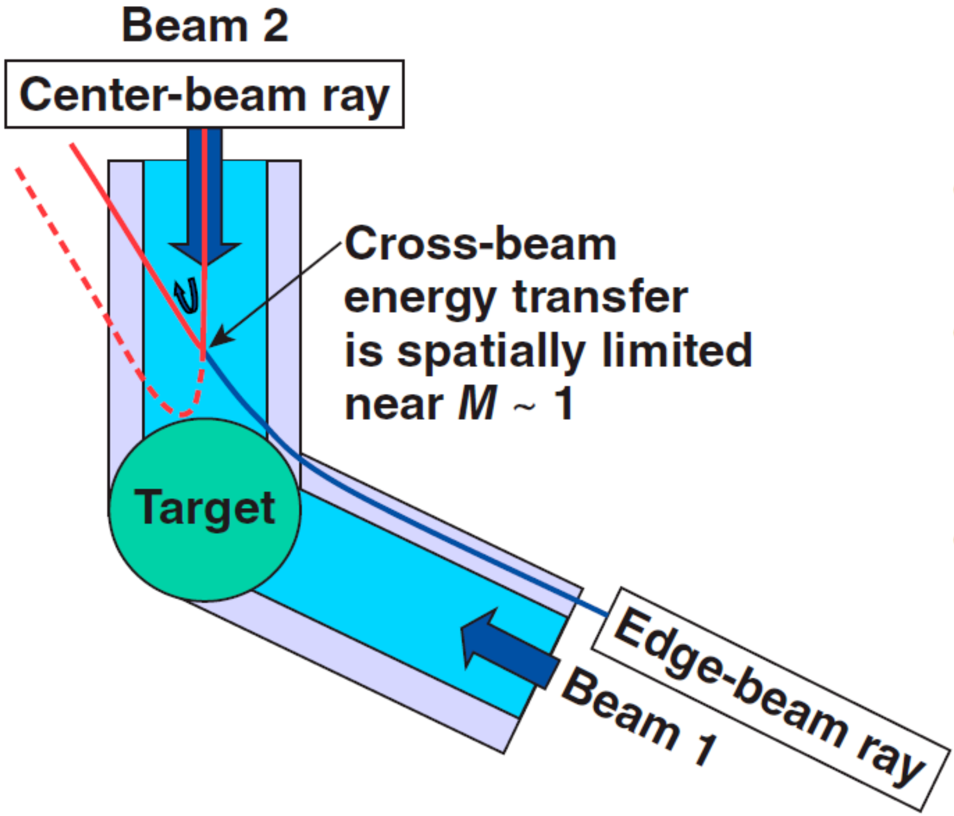


$$\chi_{no\alpha} \equiv \frac{P\tau}{P\tau_{ig}}$$

Threshold depends on the level of nonuniformities

R. Nora et al, Phys. Plasmas (2014)

The performance of direct drive capsules is currently degraded by Cross-Beam-Energy-Transfer



- CBET involves electromagnetic (EM)-seeded, low-gain stimulated Brillouin scattering
- EM seed is provided by edge-beam light
- Center-beam light transfers some of its energy to outgoing light*
- The transferred light bypasses the highest absorption region near the critical surface*

CBET reduces laser absorption and hydrodynamic efficiency.**

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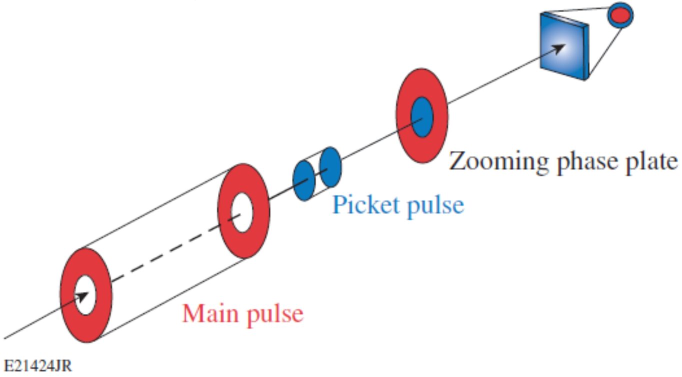
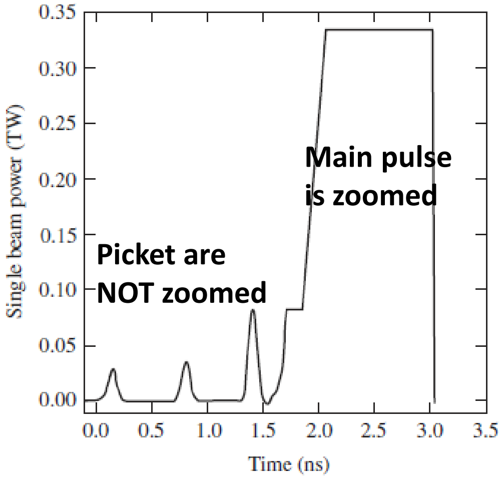
* D. H. Edgell *et al*., Bull. Am. Phys. Soc. 52, 195 (2007); 53, 168 (2008); 54, 145 (2009).

** I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

Techniques to mitigate Cross-Beam Energy Transfer include zooming phase plates and two-color split

Zooming Phase Plates[1]

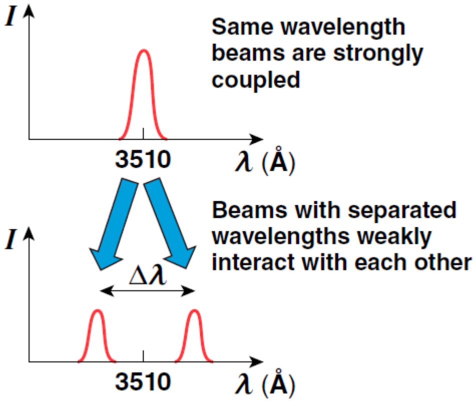




Main pulse is zoomed

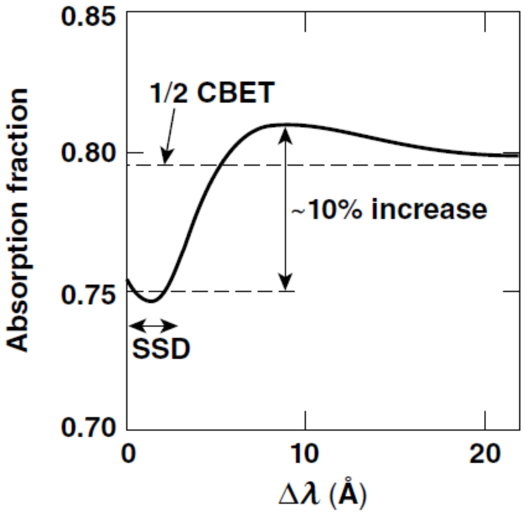
Picket are NOT zoomed

Two-color split[2]



Same wavelength beams are strongly coupled

Beams with separated wavelengths weakly interact with each other



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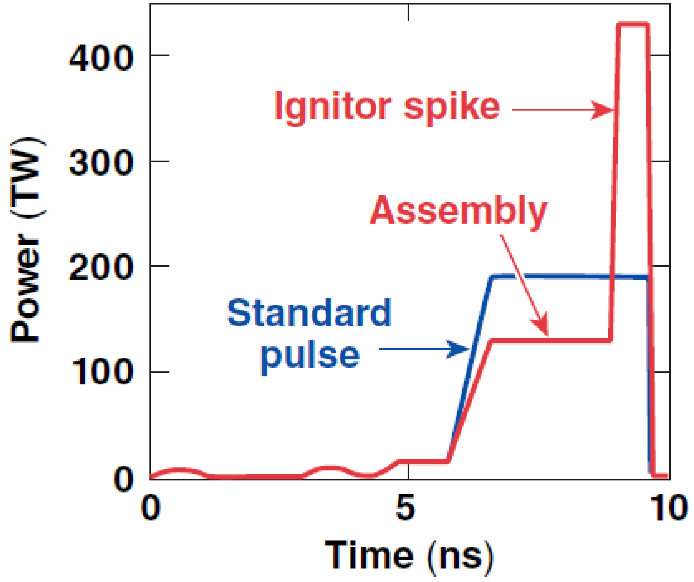
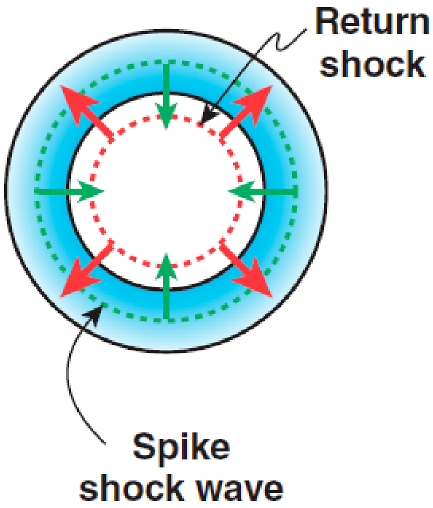
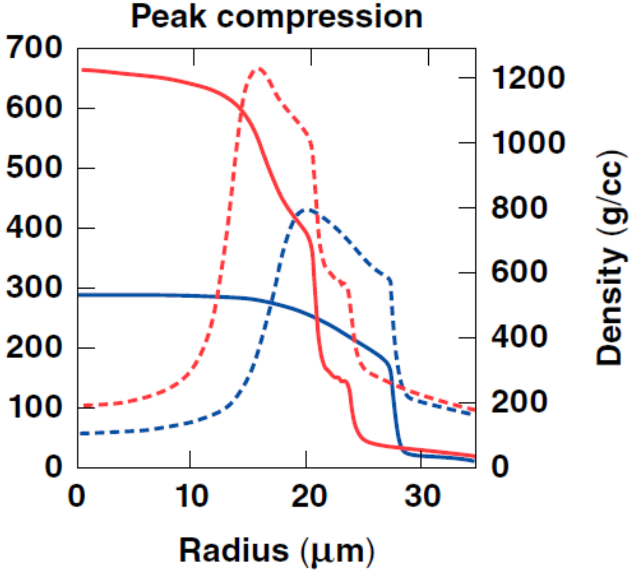
[1] D. Froula et al, submitted to Phys. Plasmas (2013)
[2] I. Igumenshchev et al, Phys. Plasmas 19, 056314 (2012)

Shock ignition is an alterative ignition scheme to achieve higher pressures than conventional ignition

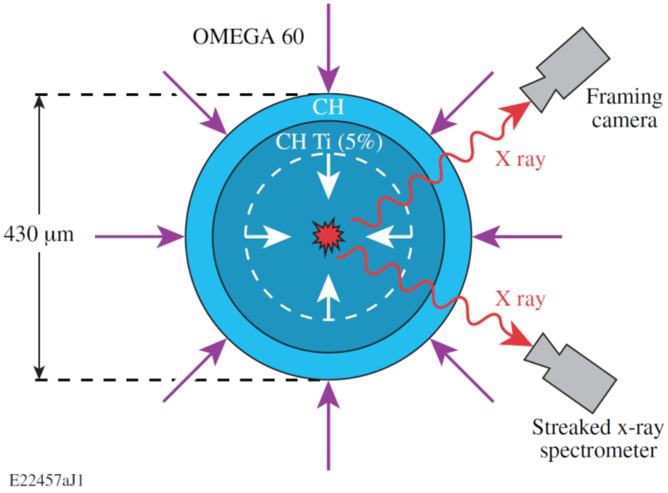


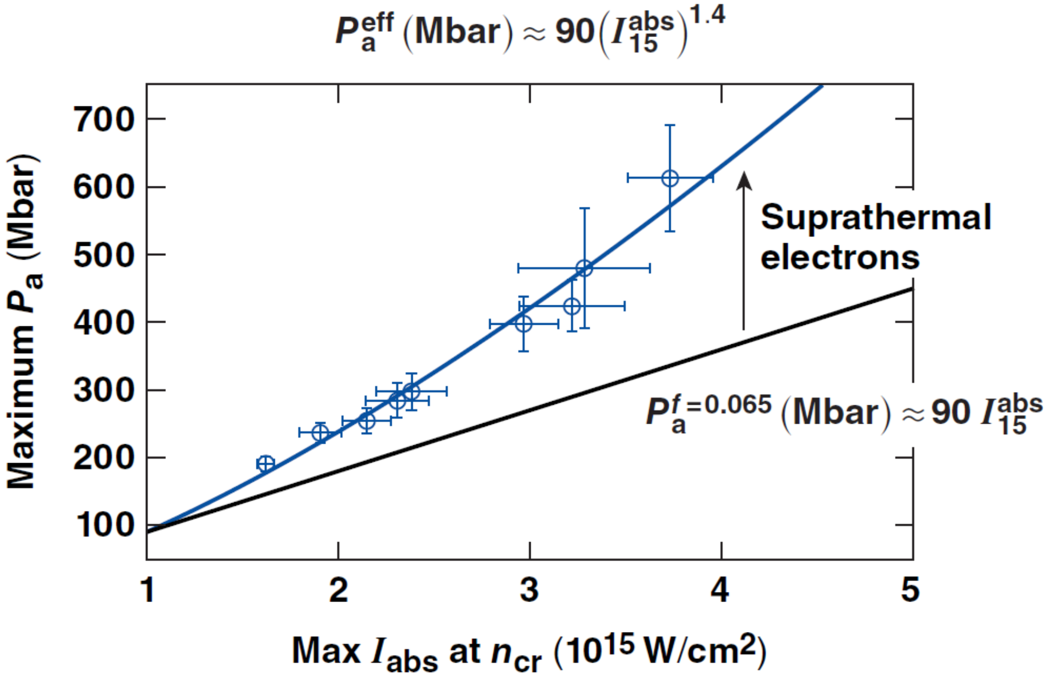




R. Betti et al, Phys. Rev. Lett. , 98, 155001 (2007)
D. Batani et al, Review, Nuclear Fusion (2014)
S. Atzeni et al, Review, Nuclear Fusion (2014)

Experimentally inferred ablation pressures above 300Mbar exceed the requirements for shock ignition





R. Nora et al, in press in Phys. Rev. Lett.

Planar experiments achieved 35-70Mbar

S. Baton et al, Phys. Rev. Lett. (2012)

M. Hohemberger et al, Phys. Plasmas (2014) conclusions

The recent results from the NIF are exciting and give hope of achieving burning plasma conditions

FSC **UR LLE**

- **Significant alpha heating of a DT plasma has been demonstrated on NIF. Estimates indicate that heating from the alphas has more than double the number of fusion reactions**
- **This is only fusion physics and reaching any conclusion about fusion energy is premature**
- **The possibility of producing a burning plasma is real and the indirect drive approach seems to be on the right path**
- **The path to ignition and gain is still uncertain, but the prospects are much brighter than ~ 12 months ago**
- **Direct-drive offers a promising alternative path to ignition and initial polar direct-drive experiments on NIF are currently under way**