How ignition and target gain > 1 was achieved in inertial fusion

O. A. Hurricane (Indirect Drive ICF Collaboration)

Arizona State University, Physics Colloquium
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9 am Pacific Coast Time

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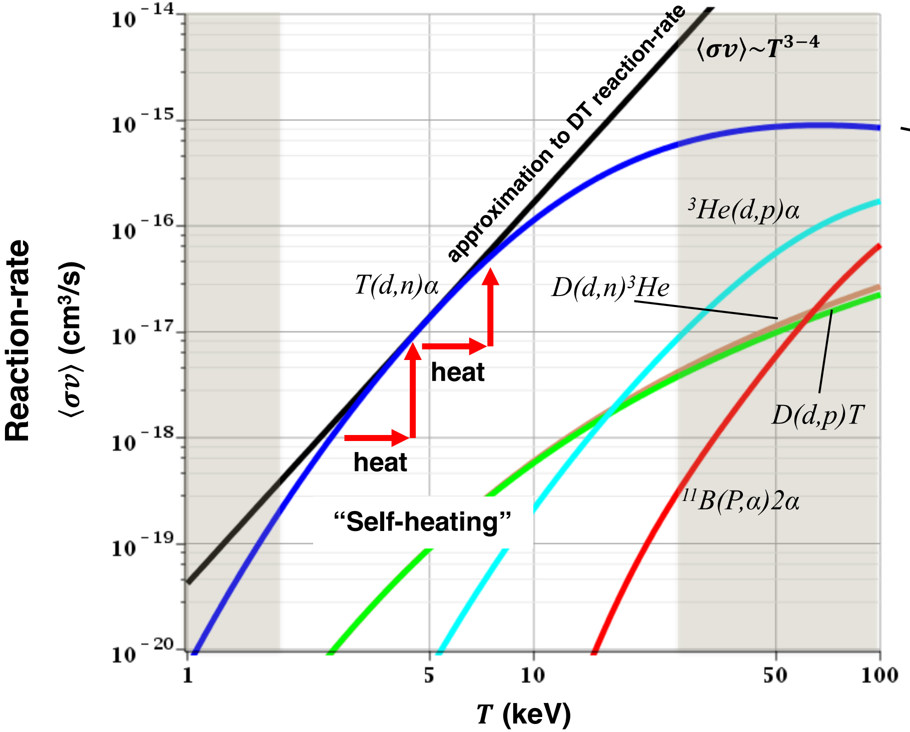
Recent NIF ICF experiments are an "existence proof" of laboratory ignition and "target gain" (G_{target}>1)

- No mystery physics obstacle stands in the way of ignition (explosive thermodynamic instability) or gain (energy out > energy in)
- The theoretical prediction of the physics parameter regime (e.g. Lawson triple product) where ignition was expected is consistent with our results
- Additional laser energy (at fixed power) was very beneficial
- Implosion physics was more sensitive to engineering control of the laser and targets than originally thought
- So far, very high gain (high compression) target designs have not worked as expected. All break-throughs over the past decade have used low gain designs
- Remarkable that we can now talk about burning plasmas, ignition, and scientific breakeven in the past-tense!

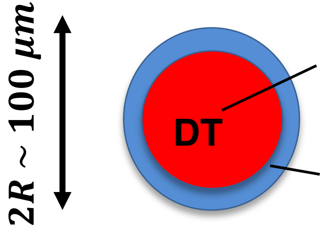
In order to get high fusion yields, we need to assemble the fusion fuel into a configuration that can stop alpha's in the fusion plasma



Fusion reaction:

helium-4 nuclei

$$D + T \rightarrow n\,(14.1\,MeV) + \alpha\,(3.5\,\text{MeV})$$



70-80% α's stopped in "hotspot" increasing T

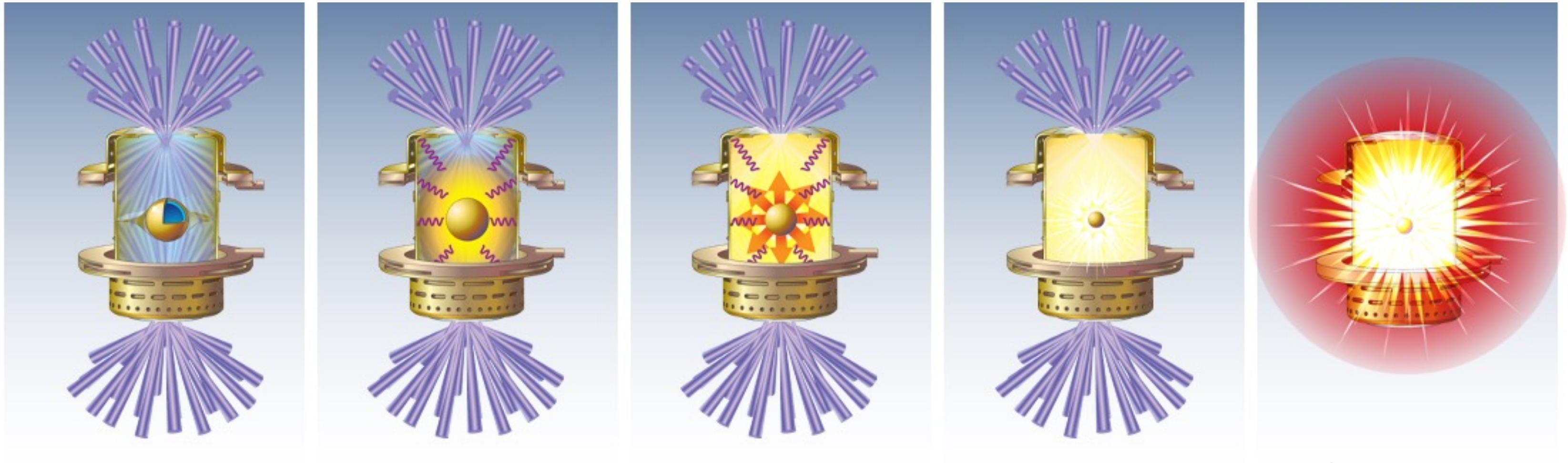
20-30% α's ablate fuel increasing hotspot mass

Conditions needed:

- hotspot areal density ($\rho R > 0.3\ g/cm^2$)
- peak central density ($\rho_{DT} > 100\ g/cc$)
- pressure ($P_{DT} > 400\ Gbar$)

If these condition are met, a thermal feed-back loop, "ignition," is generated

Indirect drive inertial confinement fusion (ICF) uses x-rays to ablate and accelerate a capsule of fusion fuel to extreme velocity



Lasers deposit energy into hohlraum

A bath of x-rays is created as the hohlraum heats

The capsule surface ablates at ~150 Mbar

The capsule accelerates inwards

Kinetic energy is converted into internal energy

“Implosion”

“Stagnation”

Achieving the conditions for ignition demands precise control of design, laser, and target parameters

e.g. Nuckolls, et al, Nature, 1972; Lindl, Phys. Plasma, 1995; Haan, et al., PoP, 2011

Often conflated, the terms "burning plasma," "ignition," and "gain" all mean something physically different

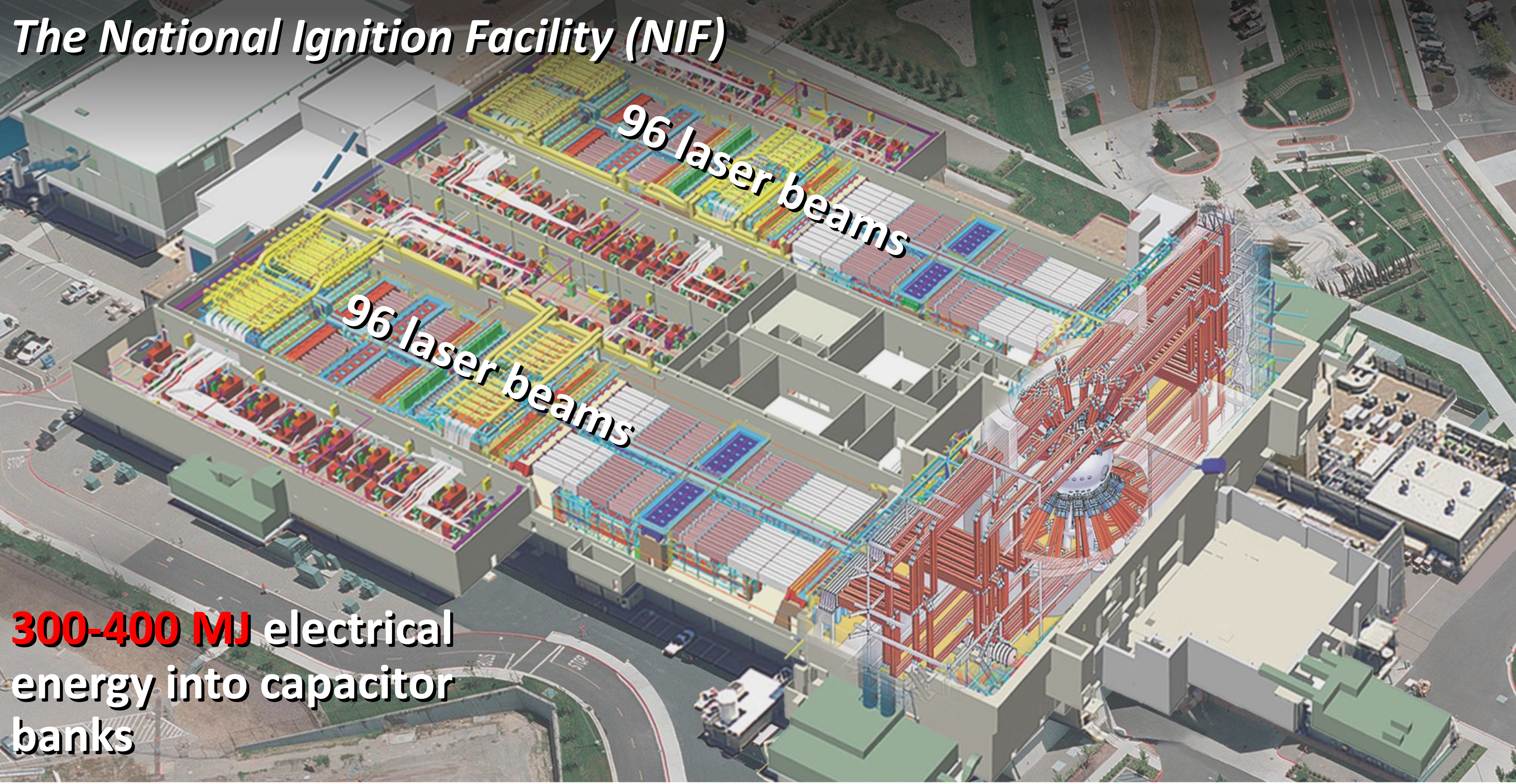
- **Burning plasma***
  - **ICF: Self-heating energy exceeds external "pdV work" to heat and compress the DT**
  - **MFE: Self-heating energy exceeds external heating of the DT**

- **Ignition (i.e. Lawson Criterion†)**
  - **Self-heating power exceeds all DT plasma power losses**
    - **Losses are radiative, electron heat conduction, negative pdV work**
  - **Results in thermodynamic instability (explosive increase in T, Y, etc).**

- **Target Gain**
  - **Fusion yield exceeds laser energy into target**
  - **1997 NAS committee used this as "ignition" in a report & the U.S. DOE adopted this definition**

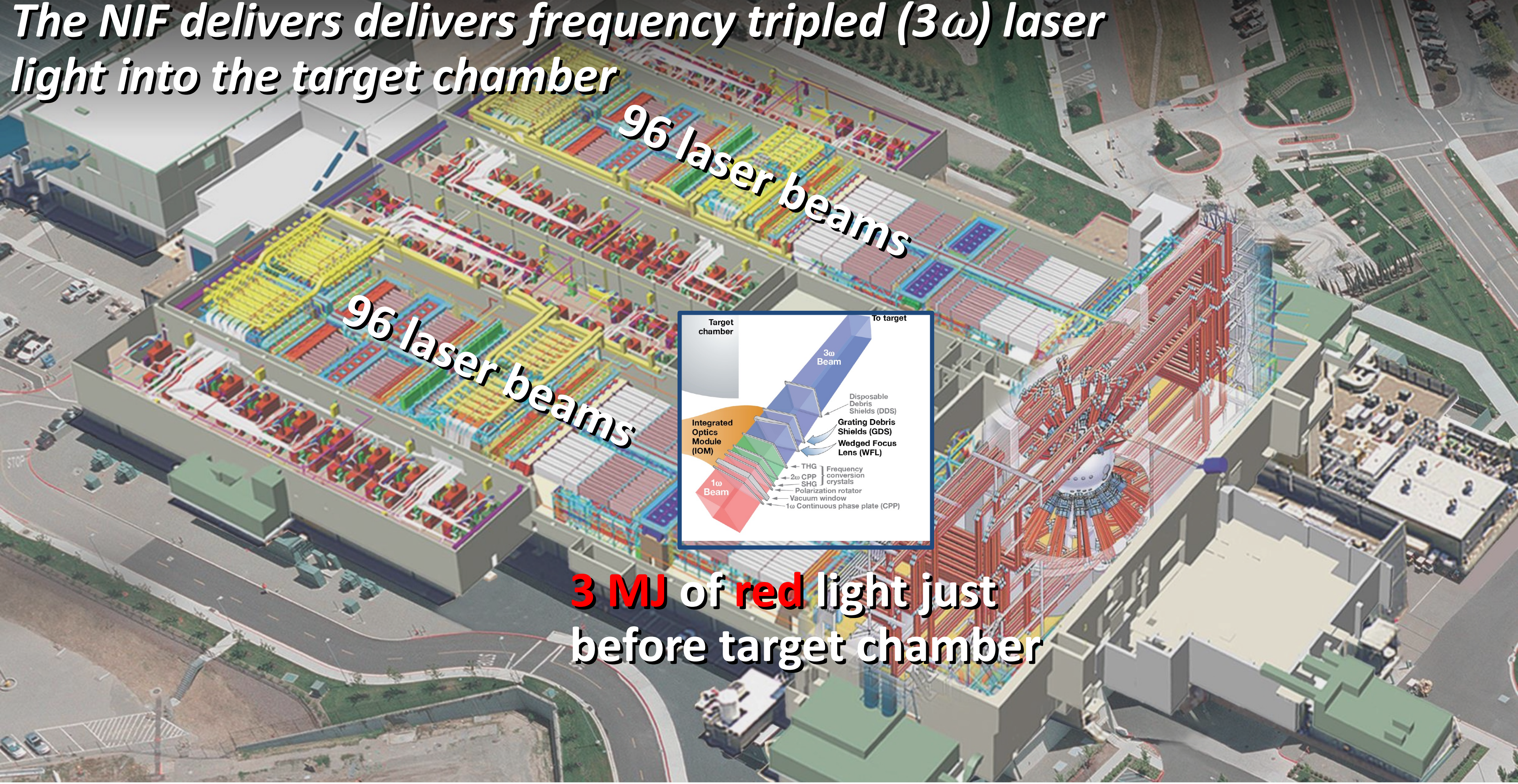
***Betti, et al, PRL, 2015; †Lawson, J.D., Proc. Phys. Soc., B, 1957**

The National Ignition Facility (NIF)



300-400 MJ electrical energy into capacitor banks

The NIF delivers delivers frequency tripled (3ω) laser light into the target chamber

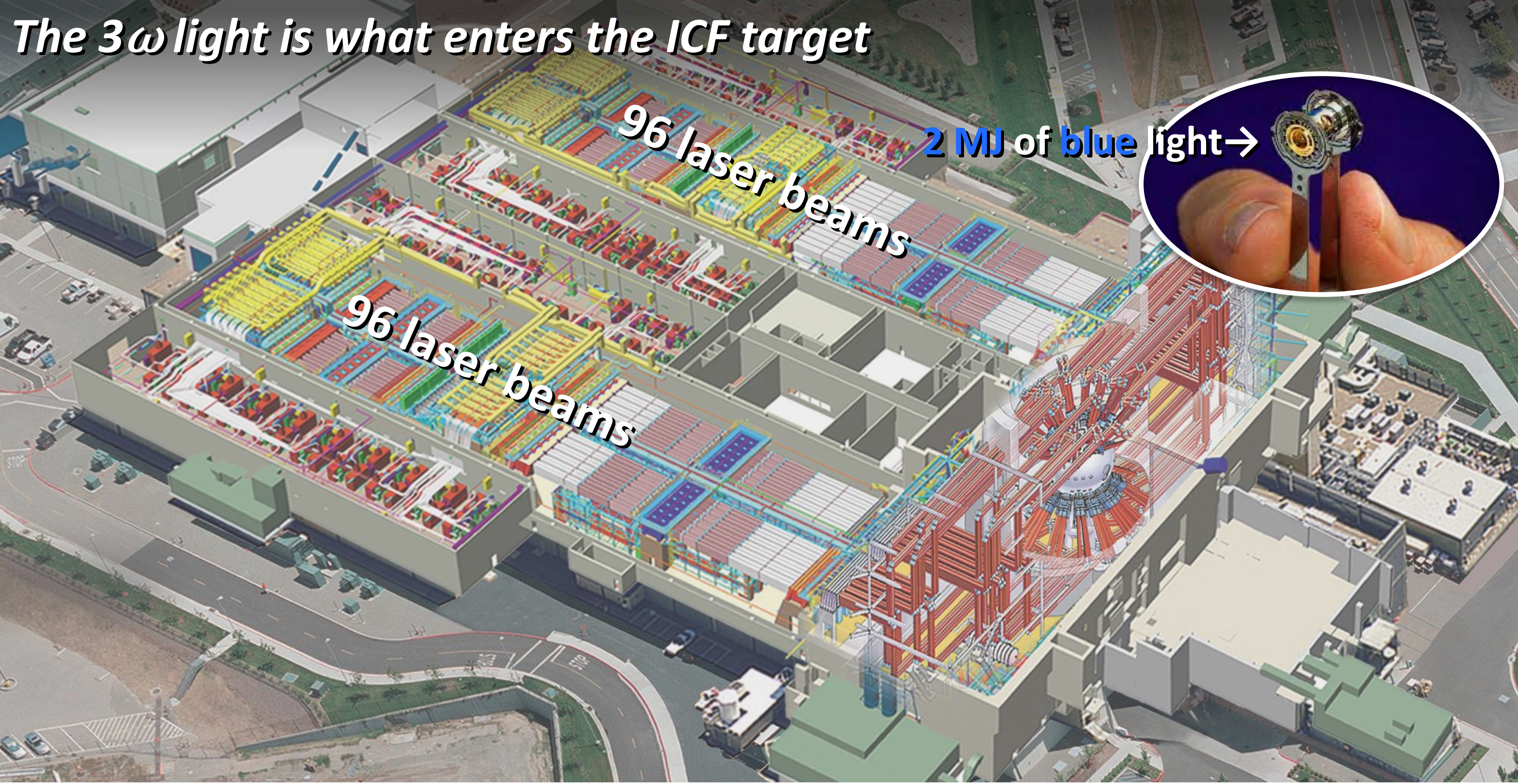


96 laser beams

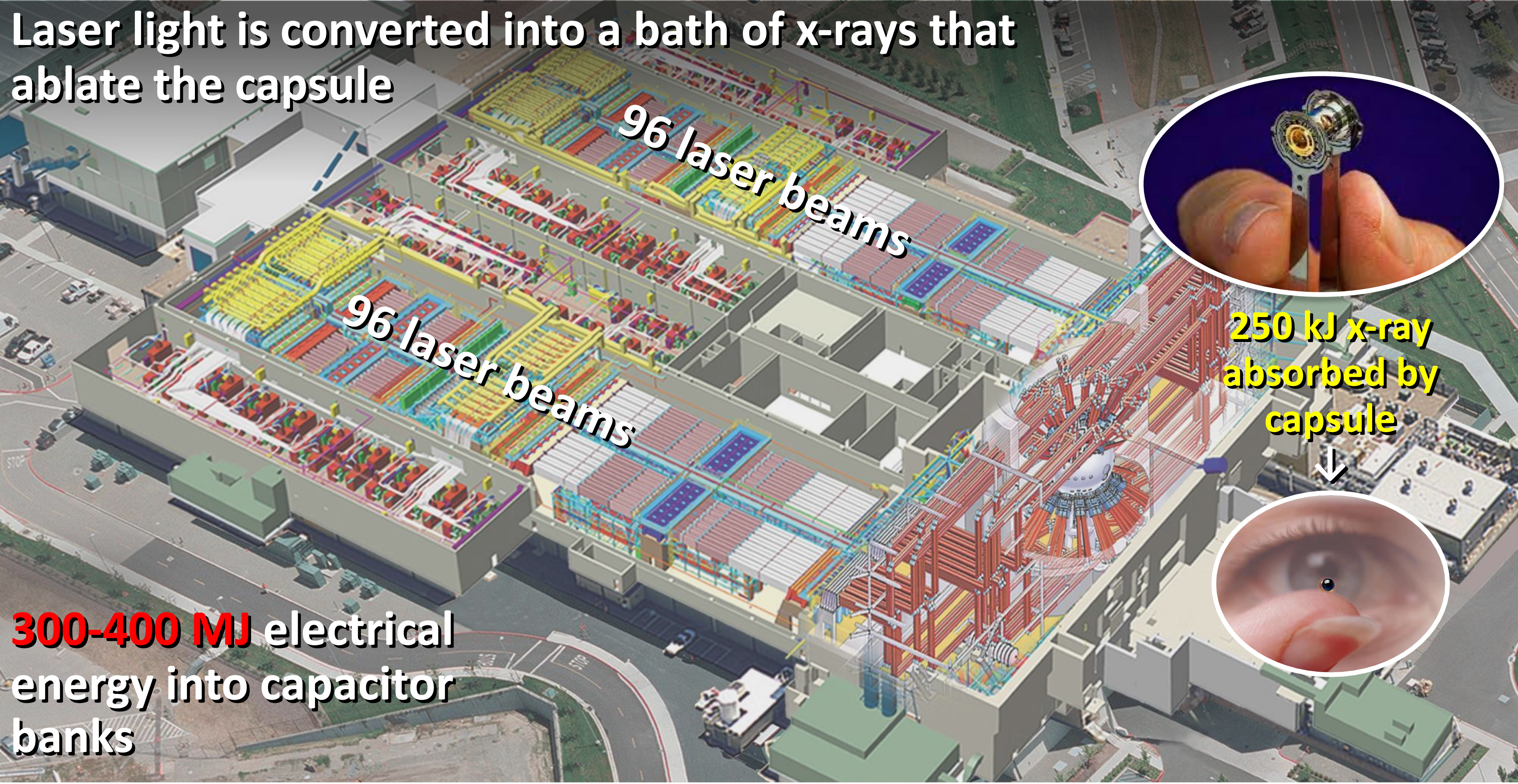
96 laser beams

3 MJ of red light just before target chamber

The 3ω light is what enters the ICF target



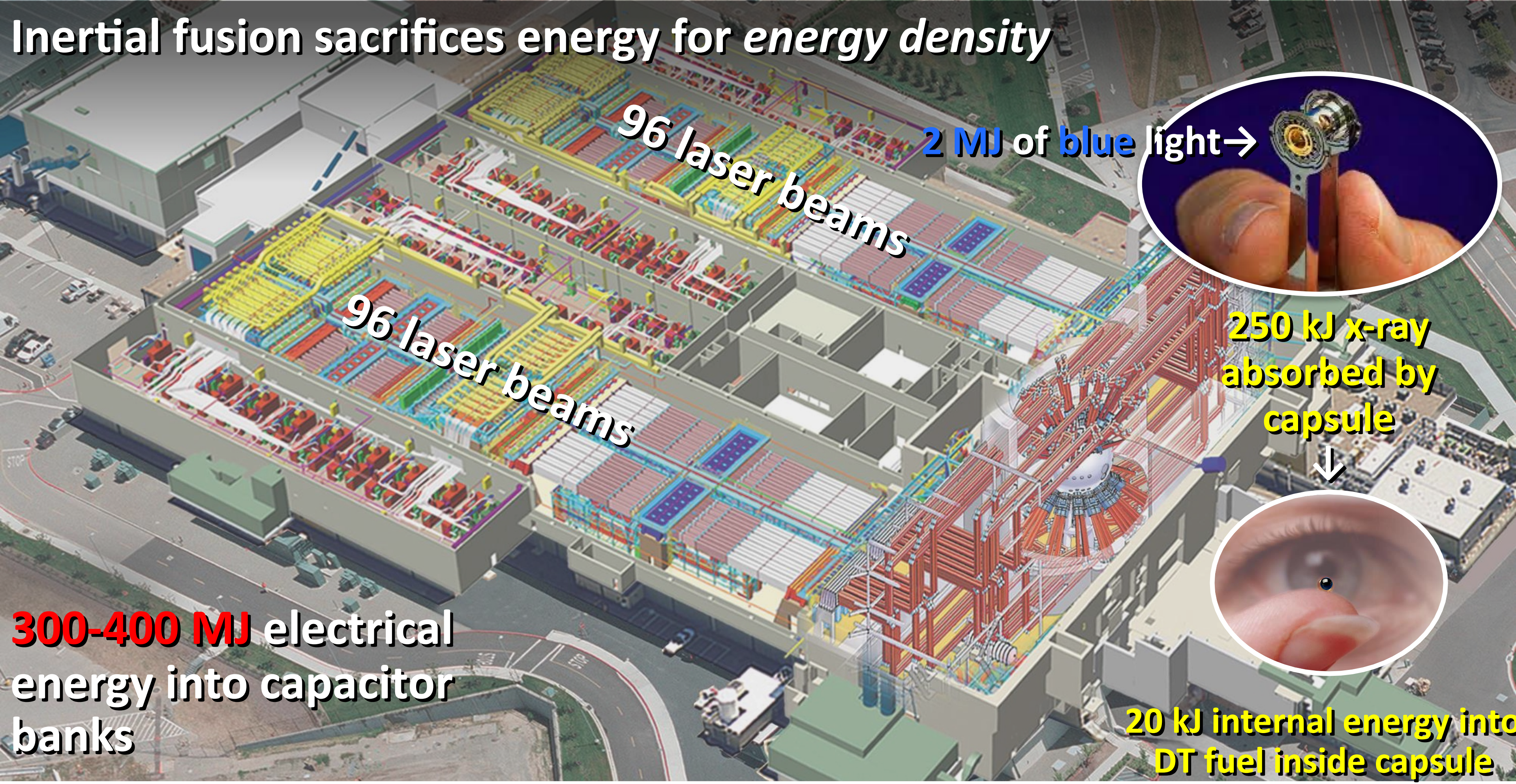
Laser light is converted into a bath of x-rays that ablate the capsule



250 kJ x-ray absorbed by capsule
↓

300-400 MJ electrical energy into capacitor banks

Inertial fusion sacrifices energy for *energy density*



96 laser beams

96 laser beams

2 MJ of blue light→

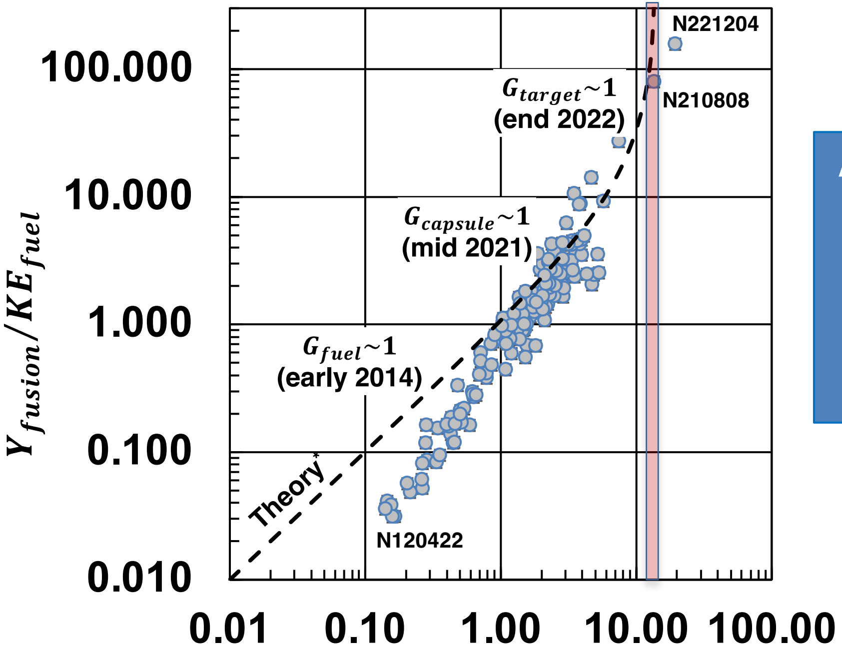
250 kJ x-ray absorbed by capsule
↓

20 kJ internal energy into DT fuel inside capsule

300-400 MJ electrical energy into capacitor banks

Most of the initial energy is lost before any gets to the fusion fuel

There are several energy gain metrics in ICF, all increased by approximately 5000x over the past decade on the NIF



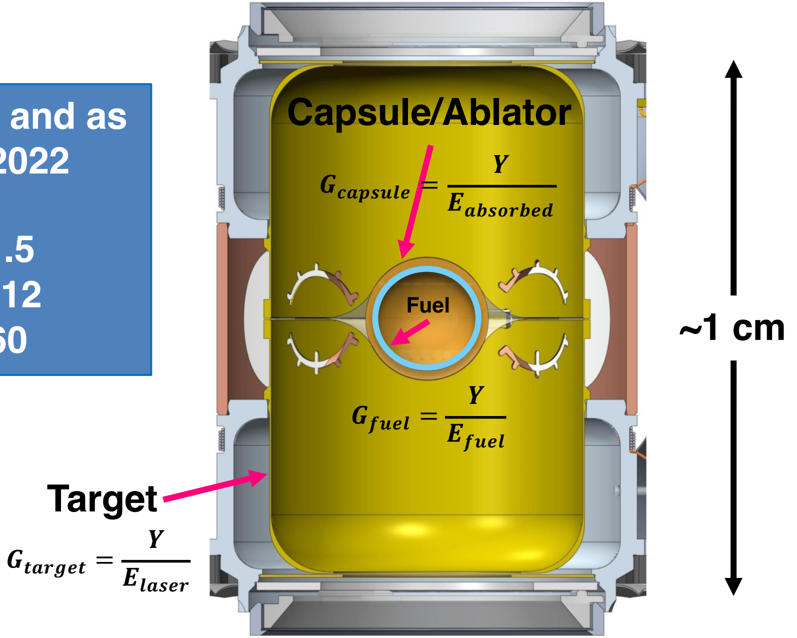
$$0.0195\,\frac{p\tau T^{1.6}}{1+\frac{E_{fuel}}{E_{hs}}}$$

Generalized Lawson Criterion (GLC) – atm-s & keV units

*Hurricane, et al, RMP in press, 2023

After 10 years and as of Dec. 5, 2022

G_{target} ~ 1.5
$G_{capsule}$ ~ 12
G_{fuel} ~ 160

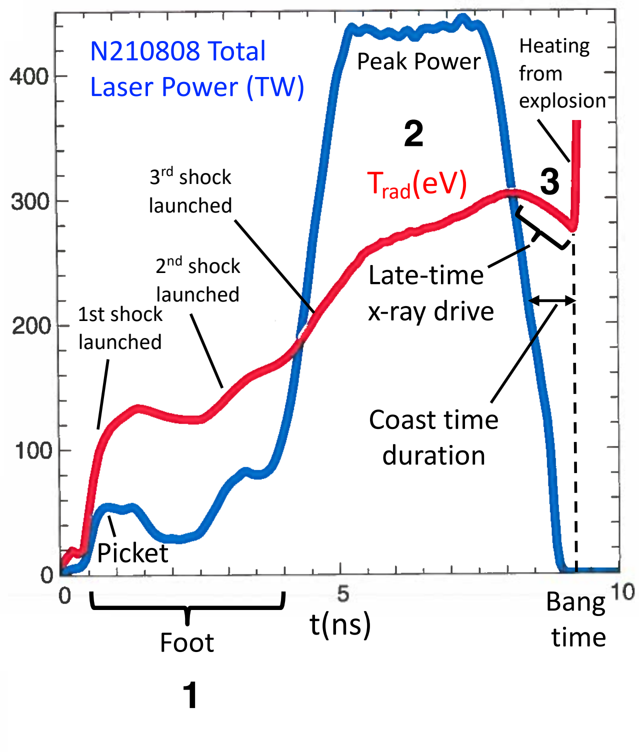


G_{target} > 1 is not “net energy gain,” because of facility energy consumption

It took a decade of work to tackle several key target physics challenges that frustrated our progress

- **Instability control**
- **Symmetry control**
- **Sufficient energy coupling**
- **Target quality**
- **Ultra-high compression**

In indirect-drive, the hohlraum, ablator, and laser pulse determine the ablation pressure that drives the implosion



Key elements of ICF laser pulse:

1. Foot – controls stability and majority of fuel entropy (adiabat, α_{if})
2. Peak Power – implosion velocity
3. Coast period – efficiency of KE conversion into DT internal energy, via radius of peak velocity

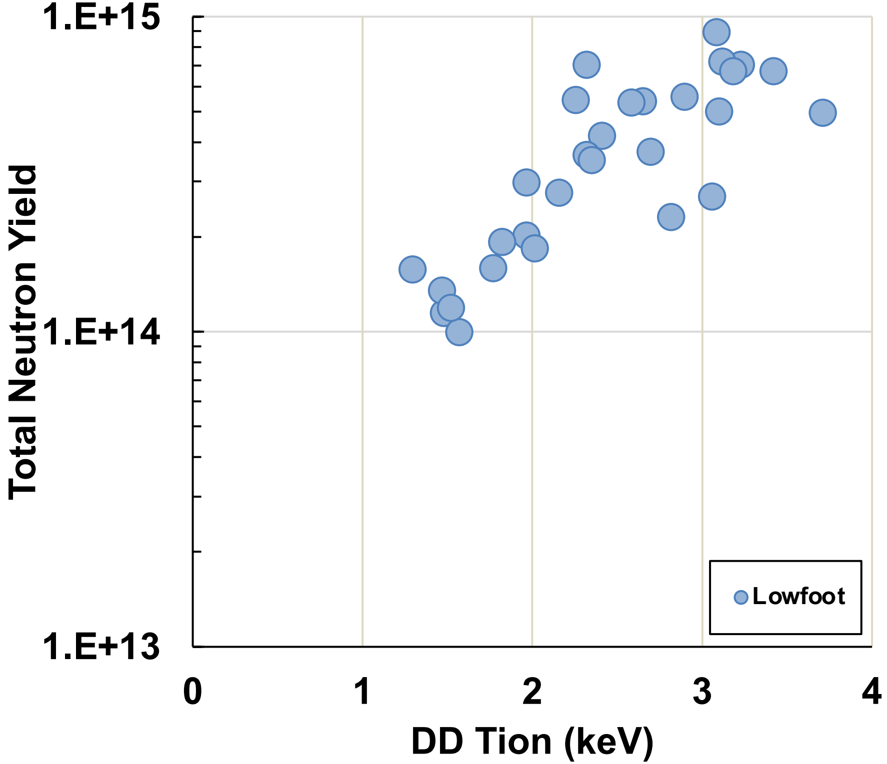
Hohlraum and laser pulse-shape

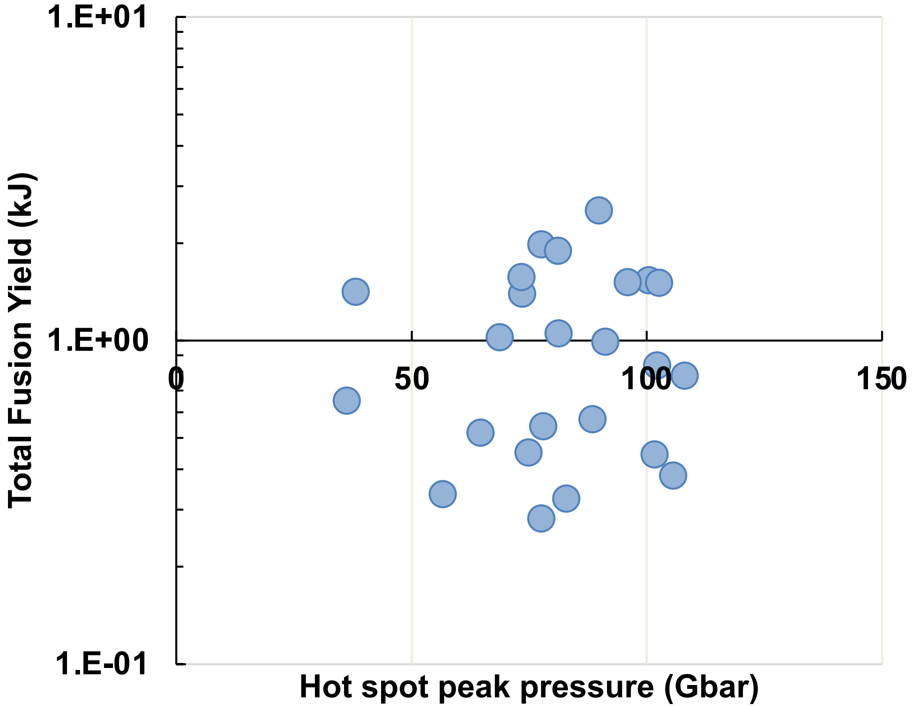
Ablation pressure on implosion:

$$p_{abl} \sim \left(\frac{\bar{A}}{\bar{Z}+1}\right)^{\frac{1}{2}} T_{rad}^{\frac{7}{2}} (1 - albedo)$$

Ablator material that forms capsule

2010-12: Plastic ablator "Low-foot" implosions were designed to be high yield (> 1 MJ), but underperformed for many reasons*





*Edwards, et al, PoP, 2013; Ma, et al., PoP, 2013; Regan et al, PRL, 2013; Lindl, et al., PoP, 2014; Clark, et al, PoP, 2016

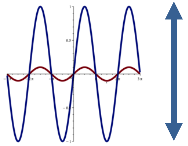
Hydro-dynamic instability defeats density and temperature gradients and is more challenging with higher compression

"Takabe" formula for linear growth rate:

$$\gamma_{A-RT} \sim \sqrt{\frac{kg}{1+kL_\rho}} - kv_{abl}$$

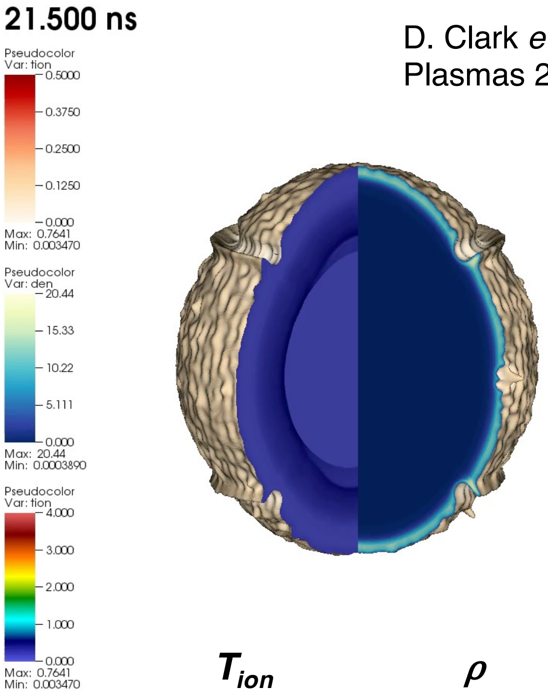
Numerous forms: e.g. Bodner, Betti, Kilkenny, Takabe, etc.

Exponential perturbation growth:



$\sim e^{\int \gamma_{A-RT} dt}$

wavelength, $\lambda = \frac{2\pi}{k}$



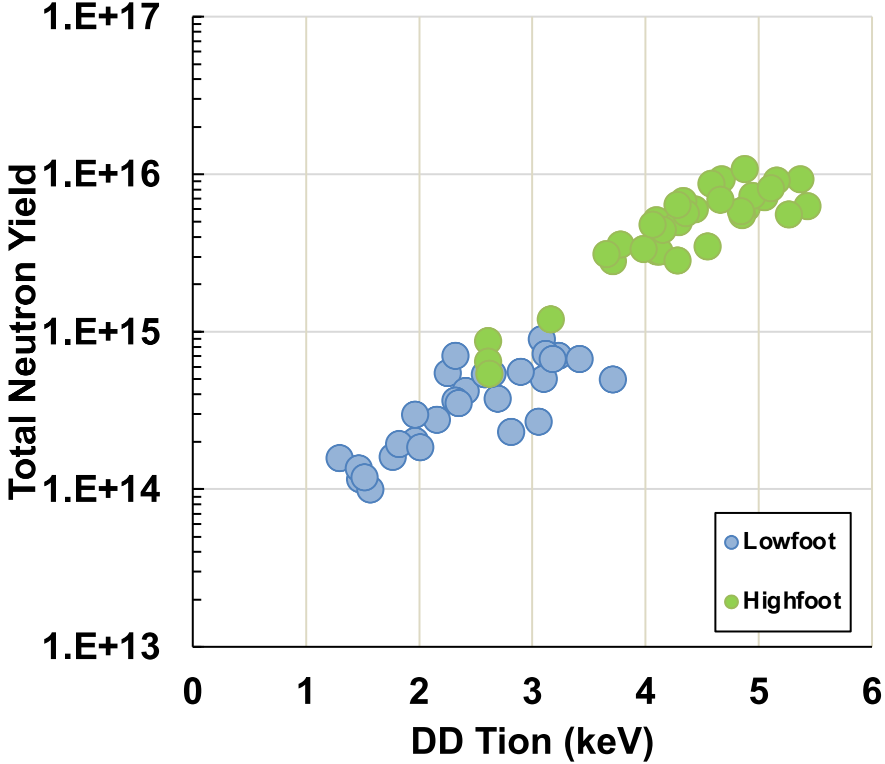
D. Clark *et al.*, Phys. Plasmas 23, 056302 (2016)

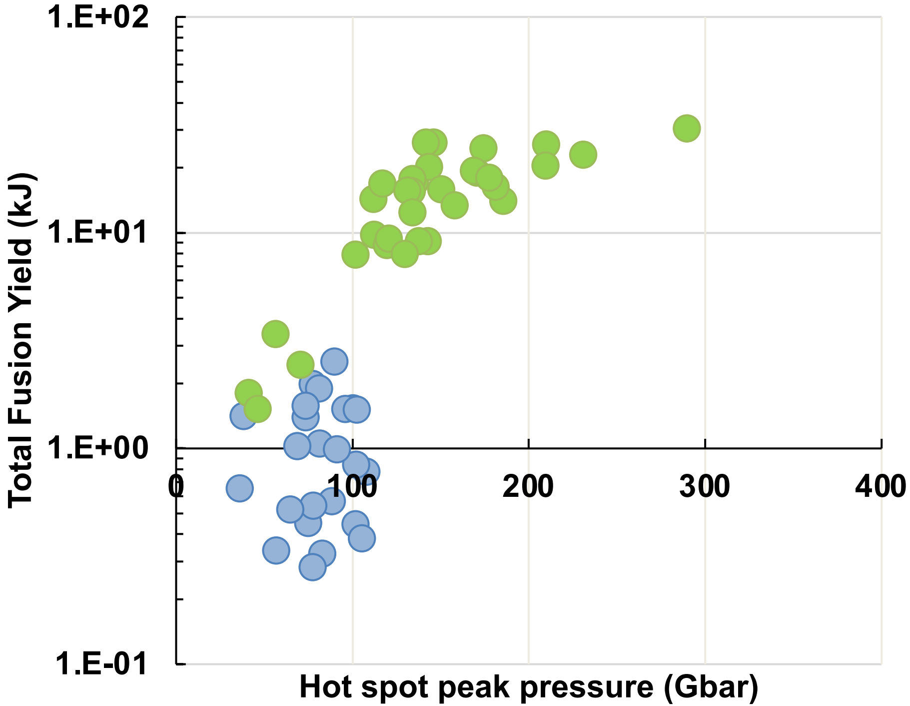
acceleration (g) is destabilizing (but how else to get high v_{imp}?)

long density gradient scale help
high ablation velocity (v_{abl}) helps

Lead to "high foot" implosion

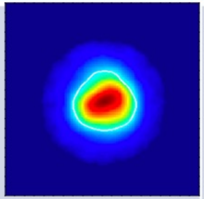
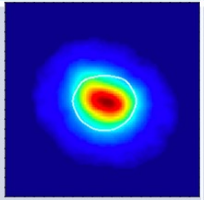
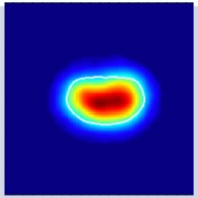
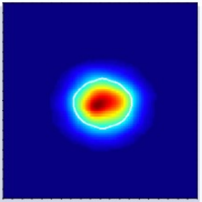
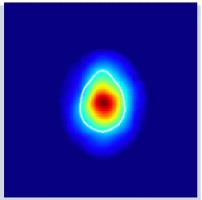
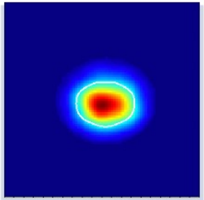
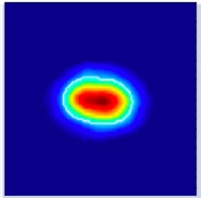
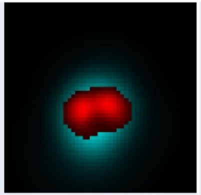
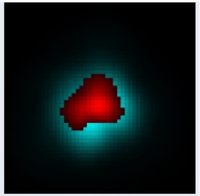
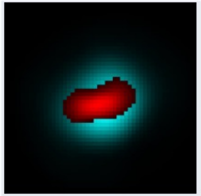
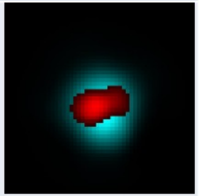
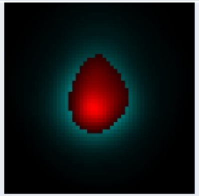
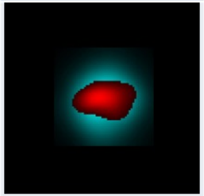
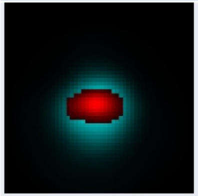
2013-2015: High-foot implosions tested if better controlling hydrodynamic instability would improve performance





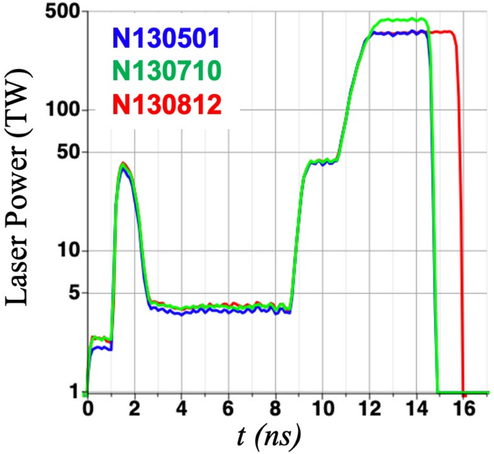
Hinkel, et al. PPCF, 2013; Dittrich, et al. PRL, 2014; Park, et al., PRL, 2014; Hurricane, et al., Nature, 2014

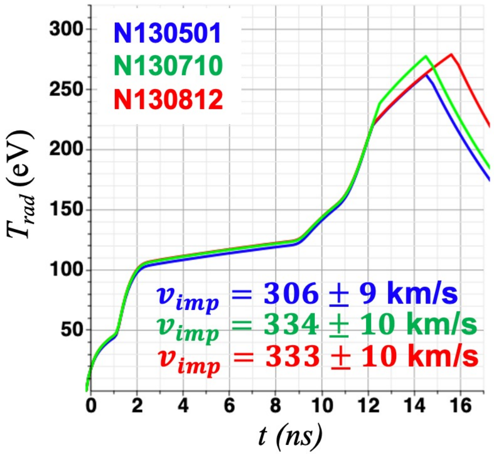
While the high foot implosions increased fusion yield by 10x and had repeatable behavior, symmetry control was an issue

High-foot DT repeatability tests	N131219	N140225 (N131219 repeat)	N141106 (N131219 repeat)	N140520	N141016 (N140520 repeat, bundle misfire)	N150121 (N140520 repeat)	N150409 (N140520 repeat)
	350 TW & 1.6 MJ			390 TW & 1.8 MJ			
X-ray emission at 78-degree view, 100x100 microns							
Neutron emission at 315-degree view (red=13-17 MeV, blue=6-12 MeV)							
Y_{total} (kJ)	9.83	9.14	9.11	25.4	10.0	20.4	22.9
T_{DT}(keV)	4.91±0.15	4.51±0.15	4.44±0.13	5.54±0.15	4.07±0.13	5.21±0.11	5.5±0.15

Spears, et al., PoP, 2014; Ma, et al, PRL, 2016; Hurricane, et al, Nat. Phys, 2016

Series of high-foot experiments revealed the importance of “coast-time” in maximizing mechanical power transfer

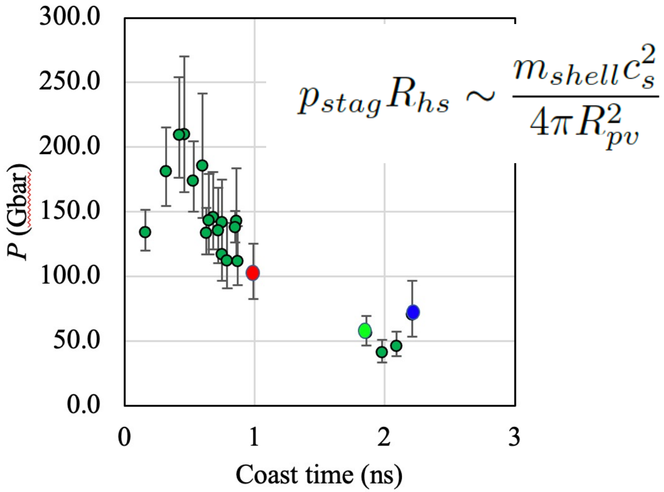




v_{imp} = 306 ± 9 km/s

v_{imp} = 334 ± 10 km/s

v_{imp} = 333 ± 10 km/s



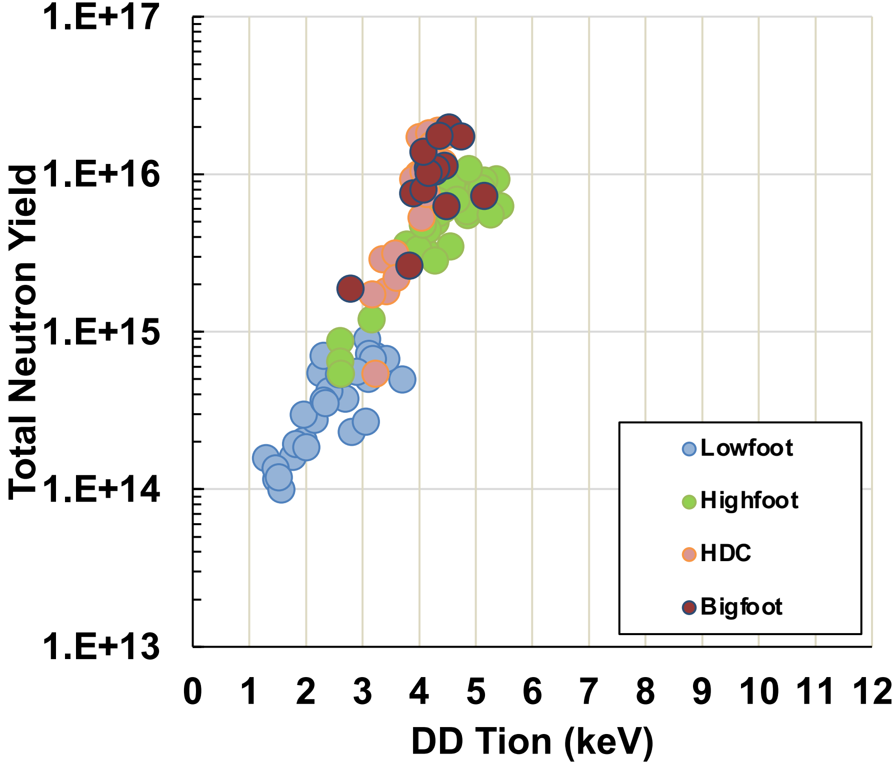
$$p_{stag} R_{hs} \sim \frac{m_{shell} c_s^2}{4\pi R_{pv}^2}$$

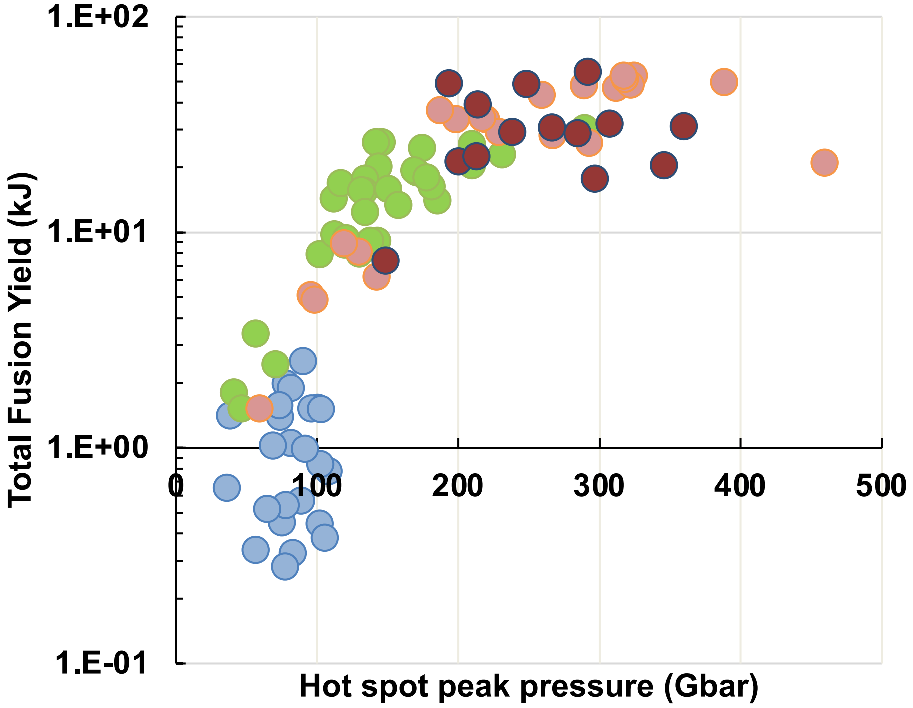
Coast-time ~ duration between max compression and end of laser pulse

Radius of peak velocity, R_{pv}, minimized with short coast-time

Hurricane, et al, PoP, 2017; Hurricane, et al, PoP, 2022

2015-2018: Higher pressures achieved using high density carbon ablators and low gas-fill hohlraums





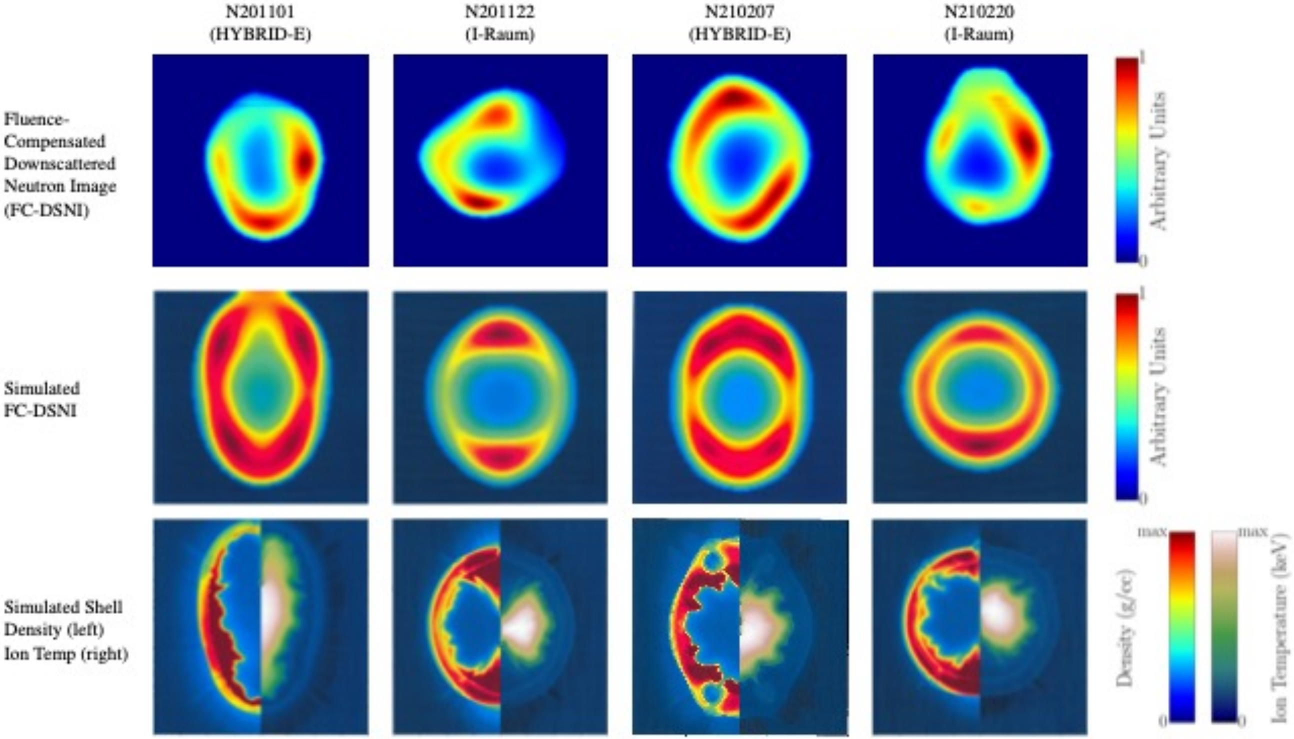
Divol, et al, PoP, 2017; LePape, et al, PRL, 2018; Berzak-Hopkins, et al, PPCF, 2018;
Casey, et al, PoP, 2018; Baker, et al, PRL, 2018; Thomas, et al., PoP, 2020

Symmetry control was improved with HDC ablators and low gas-fill hohlraums, but control is still challenging, even today

Data

Synthetic data from simulation

HYDRA* Simulation

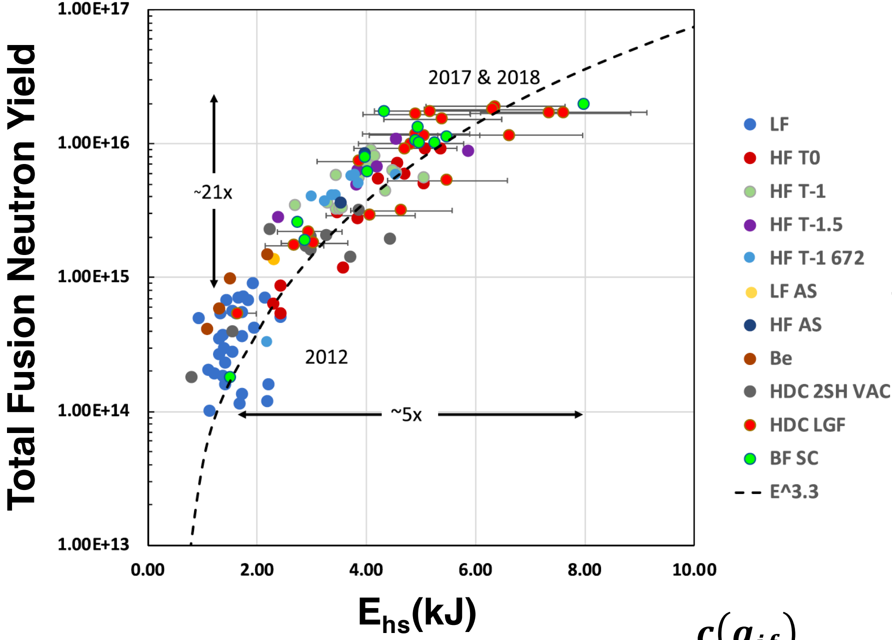


e.g. Kritcher, et al., Nature Phys. 18, 251 (2022)

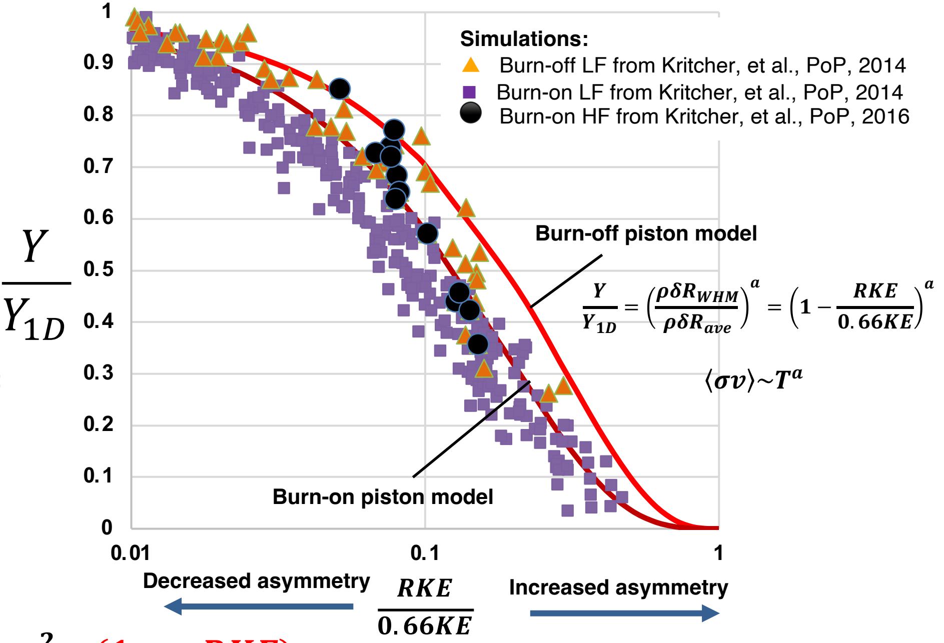
*Marinak, et al., PoP, 2003

In ICF, it is essential to maximize the conversion of implosion kinetic energy into hotspot internal energy

Experimental scaling of fusion yield with hotspot energy, $Y \sim E^{3.3}$



Degradation of fusion yield with asymmetry, $Y \sim (1\text{-}nRKE)^{3.3}$



$$\frac{Y}{Y_{1D}} = \left(\frac{\rho\delta R_{WHM}}{\rho\delta R_{ave}}\right)^{a} = \left(1 - \frac{RKE}{0.66KE}\right)^{a}$$

$$\langle\sigma v\rangle \sim T^{a}$$

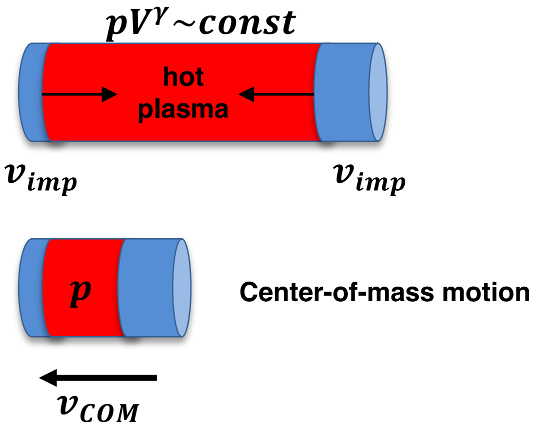
$$E_{hs} = \frac{c(a_{if})}{2} m_{shell} v_{imp}^{2} (1 - nRKE)$$

KE split into hotspot, $c(\alpha_{if}) \sim 0.66$

"HYBRID" strategy: [Hurricane, et al., PPCF 61, 014033 (2018); PoP 26, 052704 (2019)]

Implosion symmetry control is important, because it wastes kinetic energy, that could have heated the fusion fuel

Asymmetric implosion abstracted to pistons



$pV^{\gamma} \sim const$

Mode-1:

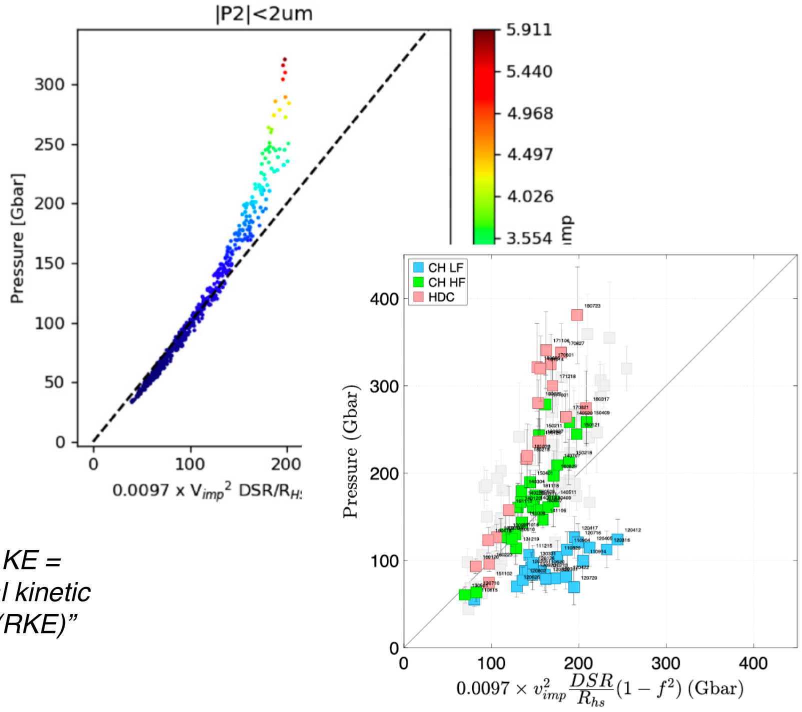
hot plasma

v_{imp} v_{imp}

p

Center-of-mass motion

v_{COM}



From conservation of energy and momentum:

$$p = \frac{1}{3}\frac{m_{pistons} v_{imp}^2}{V}\left(1 - \frac{v_{com}^2}{v_{imp}^2}\right)$$

minimum hot volume

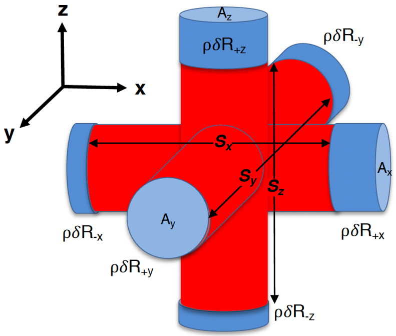
"wasted" KE

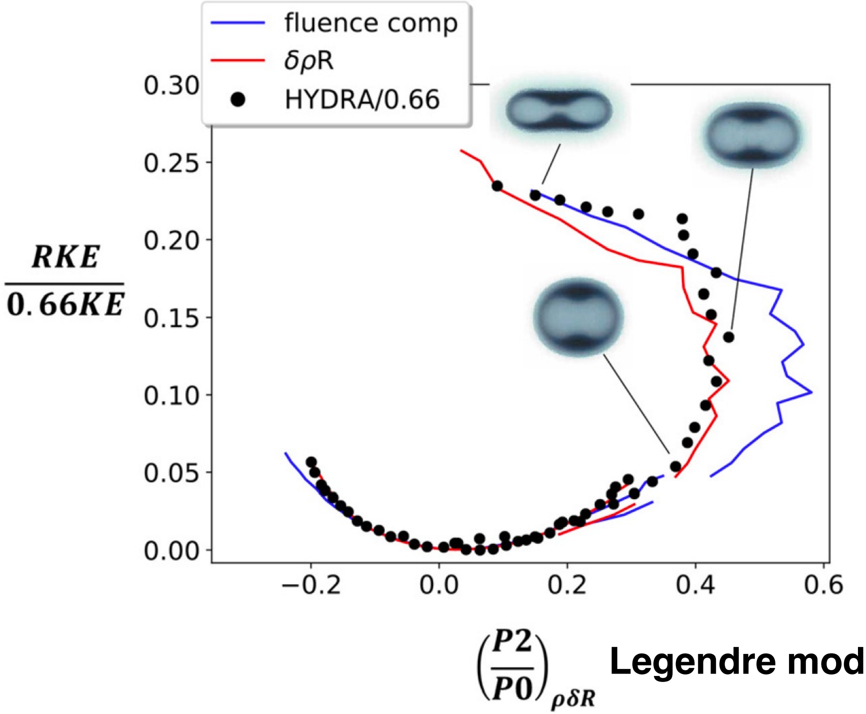
Wasted KE = "residual kinetic energy (RKE)"

Hurricane, et al, PoP, 2020, Casey, et al, PRL, 2021; MacGowan, et al, HEDP, 2022

Asymmetry wastes kinetic energy, even when there is no net center of mass motion

Mode-2:





Legendre mode 2

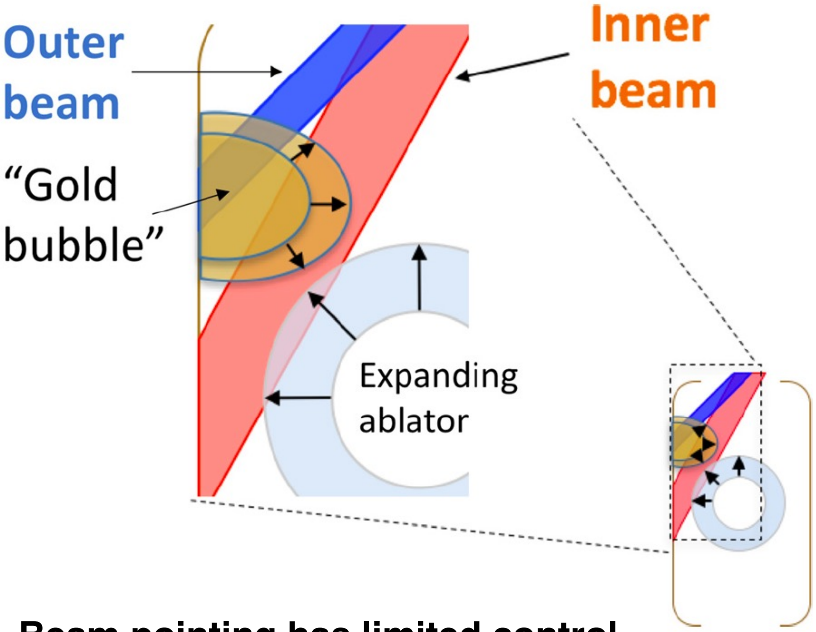
Key parameter for 3D asymmetry:

$$\frac{\rho\delta R_{WHM}}{\rho\delta R_{ave}} = \frac{\left(\int dA\right)^2}{\left(\int \frac{dA}{\rho\delta R}\right)\left(\int \rho\delta R dA\right)}$$

WHM = weighted harmonic mean* of shell areal density

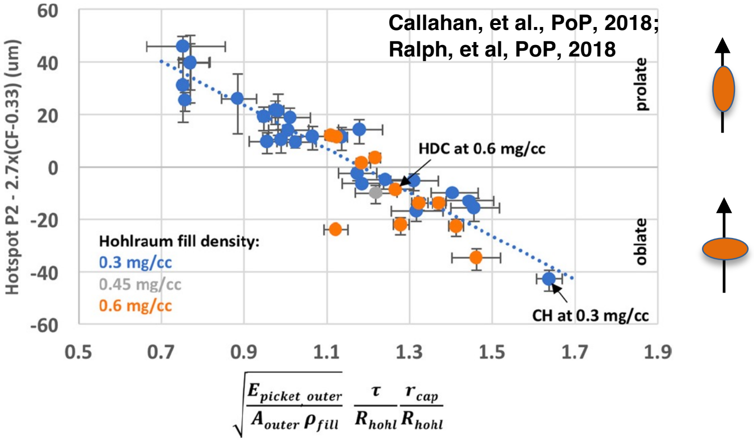
***Hurricane, et al, PoP, 2022; Betti & Woo, PoP, 2021**

Significantly improved understanding of the levers controlling implosion symmetry obtained during the 2015-2018 period



Beam pointing has limited control

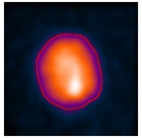
Legendre mode-2 ("P2") scaling:



Cross-beam energy transfer with low gas-fill:

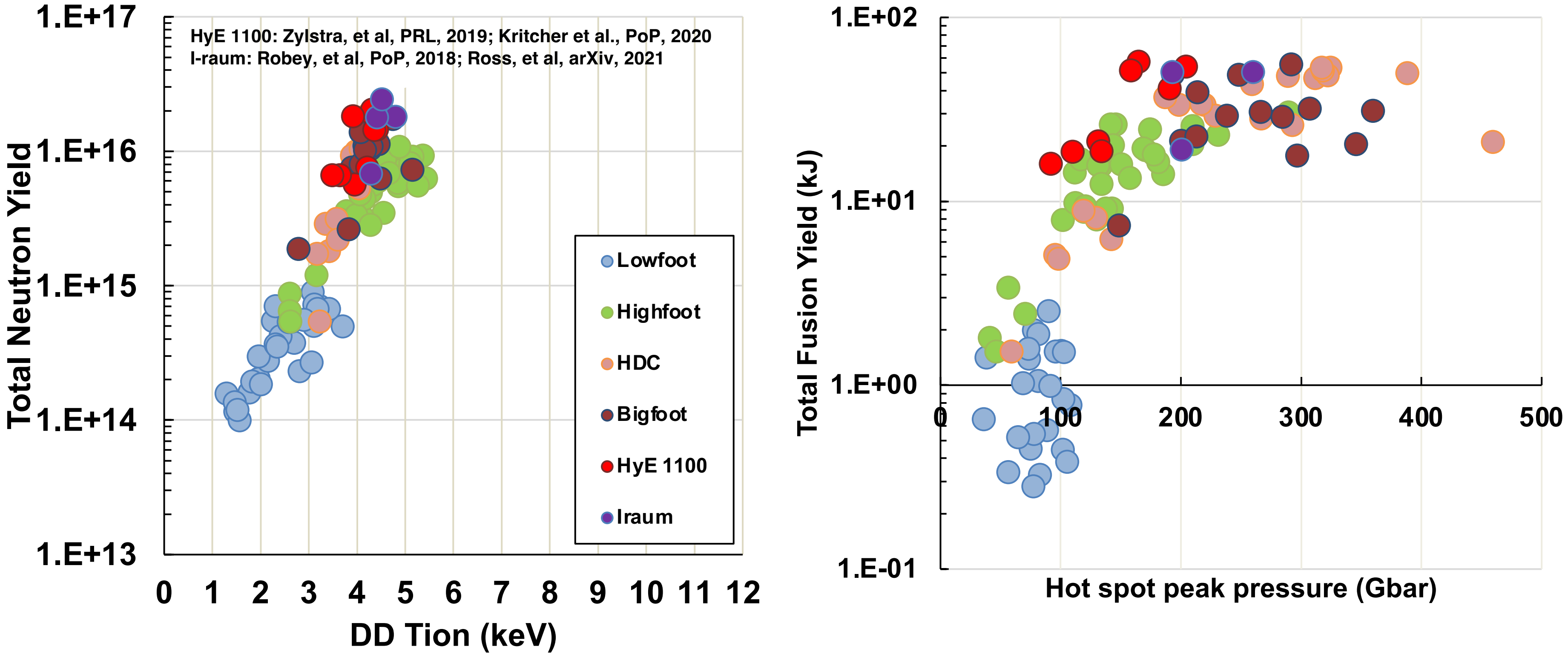
$\Delta\lambda = 0\text{Å}$

$\Delta\lambda = 1\text{Å}$



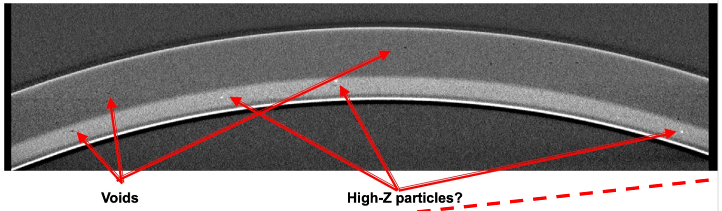
A. L. Kritcher, et al *Phys. Rev. E* 98, 053206 (2018); L. Pickworth, et al, PoP (2020)

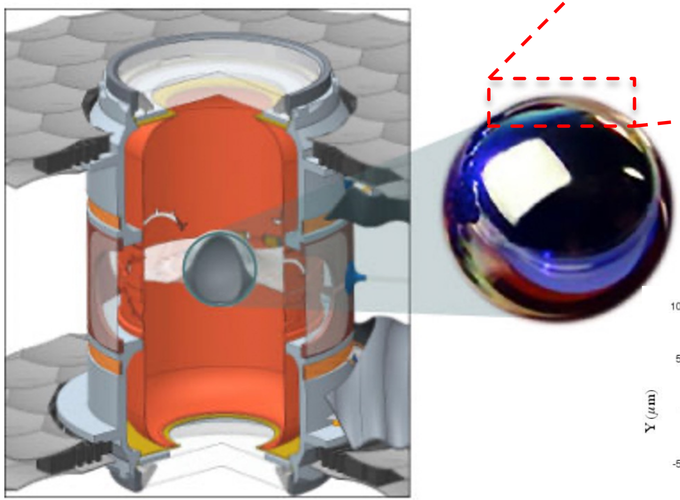
2018-2020: With a better understanding of the levers on capsule and hohlraum control, we scaled up capsule radius, but ...

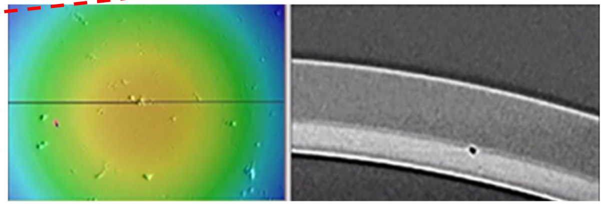


... initially this strategy struggled

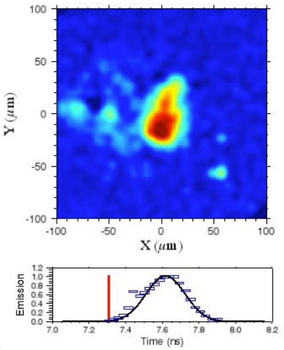
We got surprised by numerous capsule defects when we increased capsule radius … problems identified (as shown) and eventually resolved

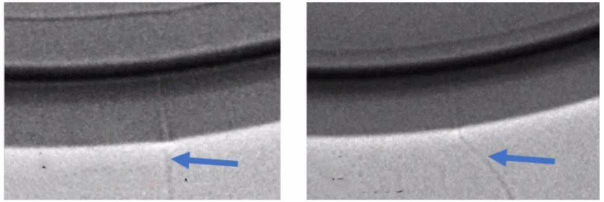






(Left) Confocal microscope image showing pits on the capsule surface. (Right) Tomographic image showing an internal void.





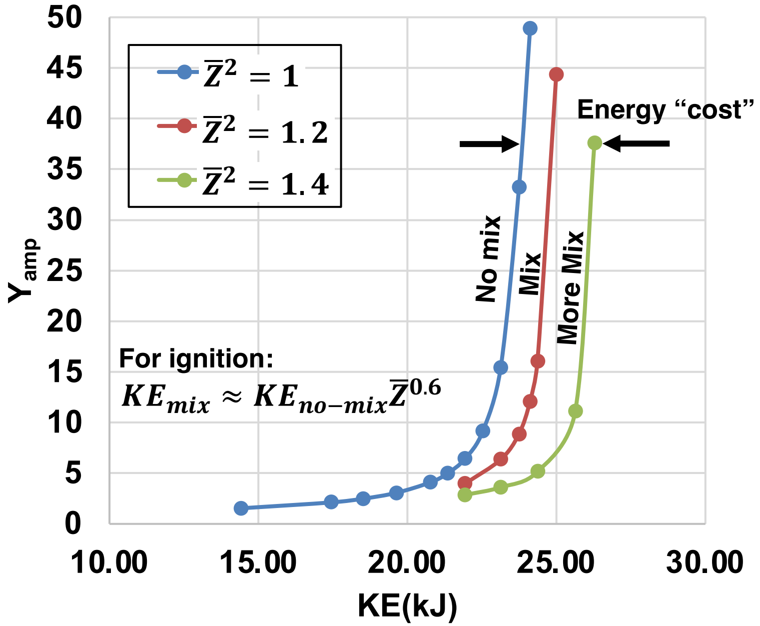
(Left) The five-micron fill tube used in the Feb. 7, 2021, experiment (an average human hair is about 70 microns in diameter). (Right) The two-micron tube used on Aug. 8. The thinner tubes are challenging to fabricate and extremely fragile, as shown by the bend that develops as the capsule cools.

Slide courtesy T. Braun, LLNL target fabrication

Braun, et al., Nuclear Fusion, 63, 2022

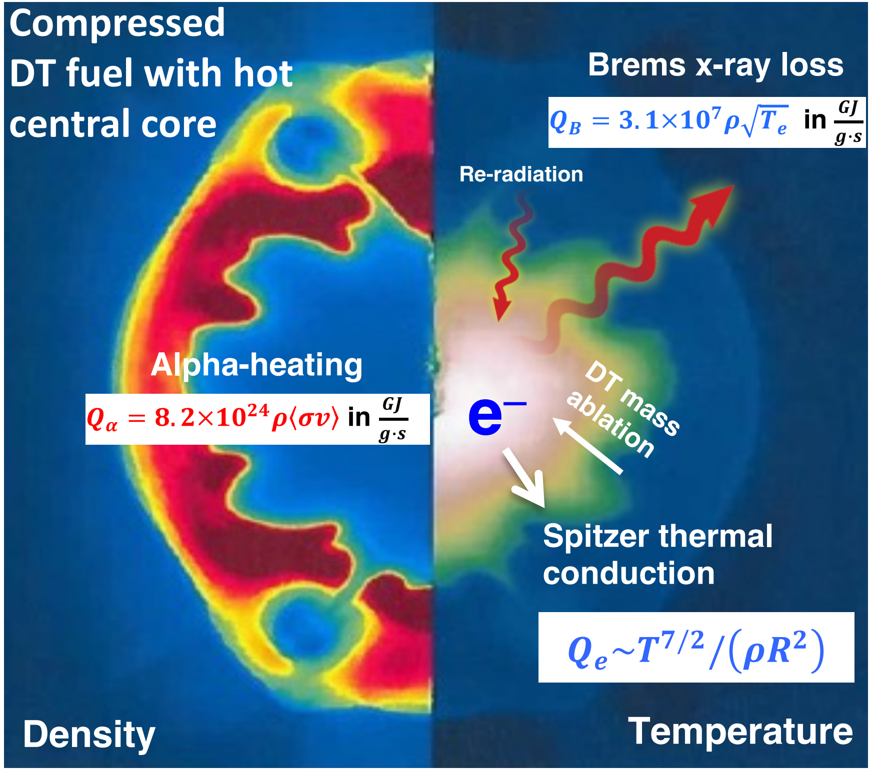
More mixing (from capsule defects + hydro) costs energy, putting more demands upon the driver

Energy and Yield amplification "cost" of mix for N210808-like implosion



For ignition:

$$KE_{mix} \approx KE_{no-mix}\bar{Z}^{0.6}$$

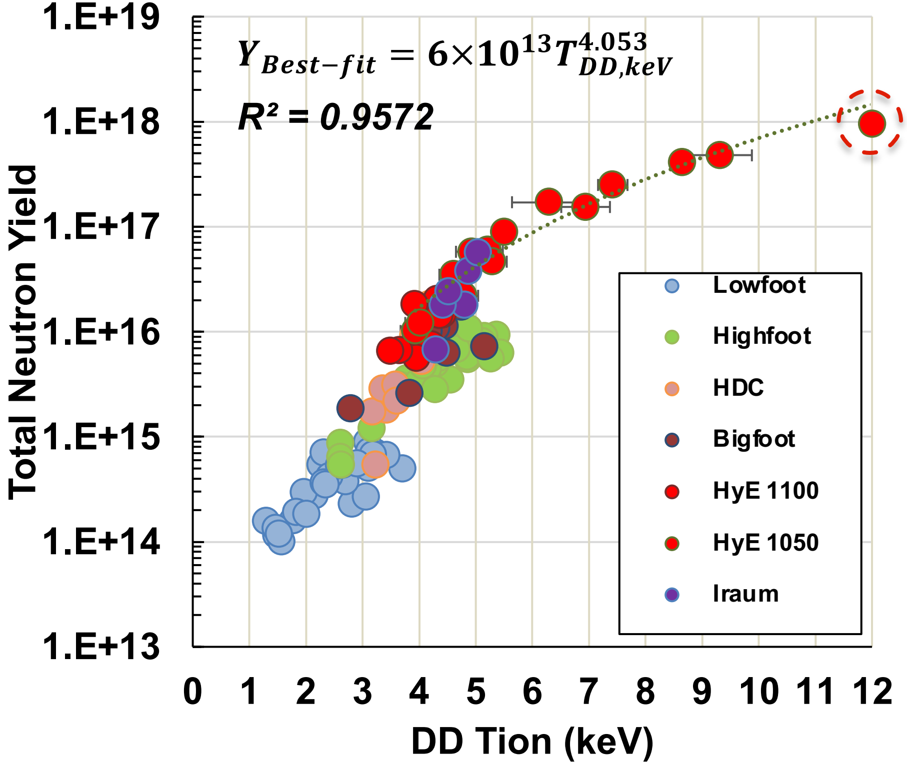


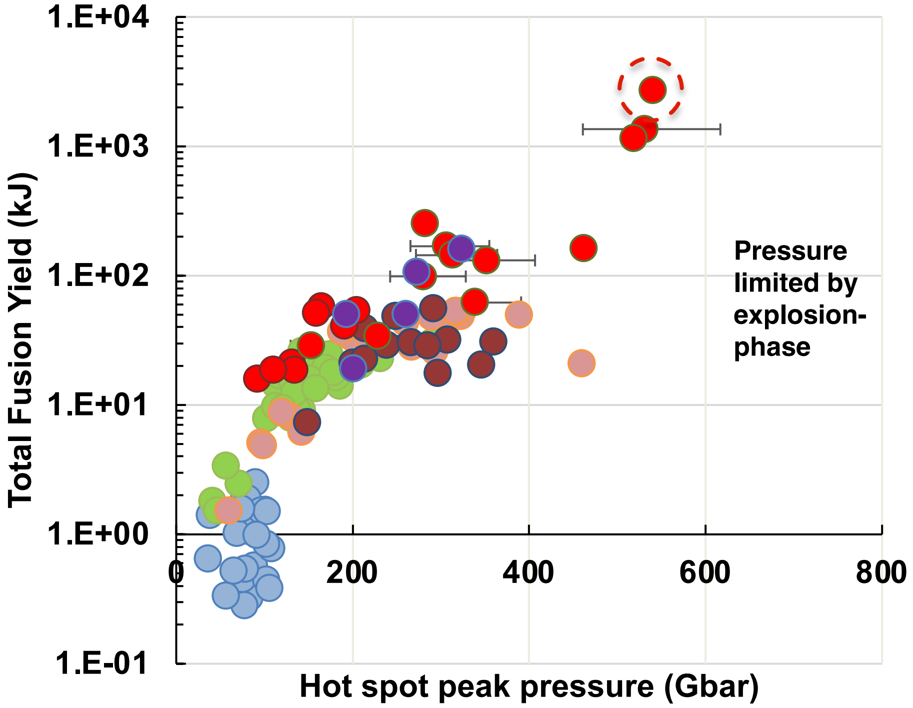
$Q_B = 3.1\times10^7\rho\sqrt{T_e}$ in $\frac{GJ}{g\cdot s}$

$Q_\alpha = 8.2\times10^{24}\rho\langle\sigma v\rangle$ in $\frac{GJ}{g\cdot s}$

$Q_e \sim T^{7/2}/(\rho R^2)$

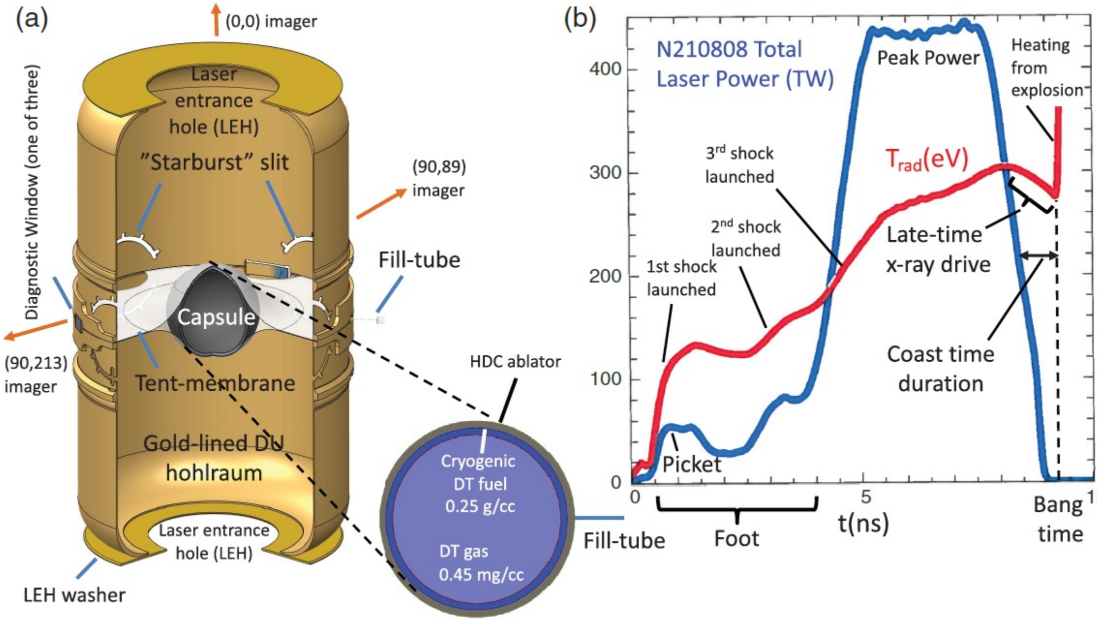
After years of effort, we got more energy from the NIF laser (1.9 MJ → 2.05 MJ), enabling the most recent success





By addressing problems *in steps* and using a basic principles understanding, coupled with design optimization and finesse, went from 1.5 kJ to 3.15 MJ fusion yield

HYBRID-E is the first ICF design to obtain a burning plasma[1] and ignition[2] in the laboratory



Key elements:

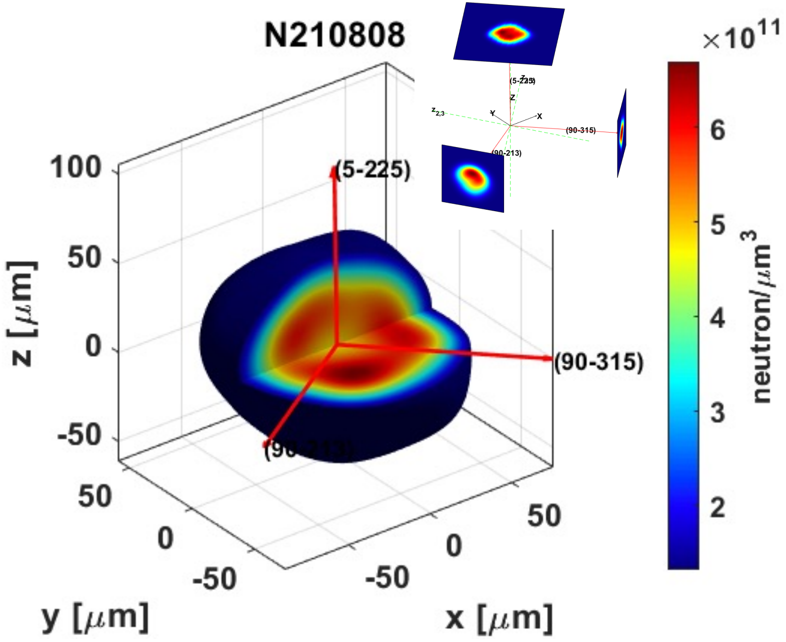
- Up to 20% larger radius capsule than previous HDC ablator designs
- Reduced LEH size, for better x-ray confinement[3], with symmetry control via CBET[4]/pointing
- Lower laser peak power, but an extended duration of peak power in order to reduce "coast time" duration[5]
- All resulting in increased hotspot energy and pressure

[2] Abu-Shawareb, et al (Indirect Drive ICF Collaboration), PRL, 2021; Kritcher, et al, PRE, 2021; Zylstra, et al, PRE, 2021

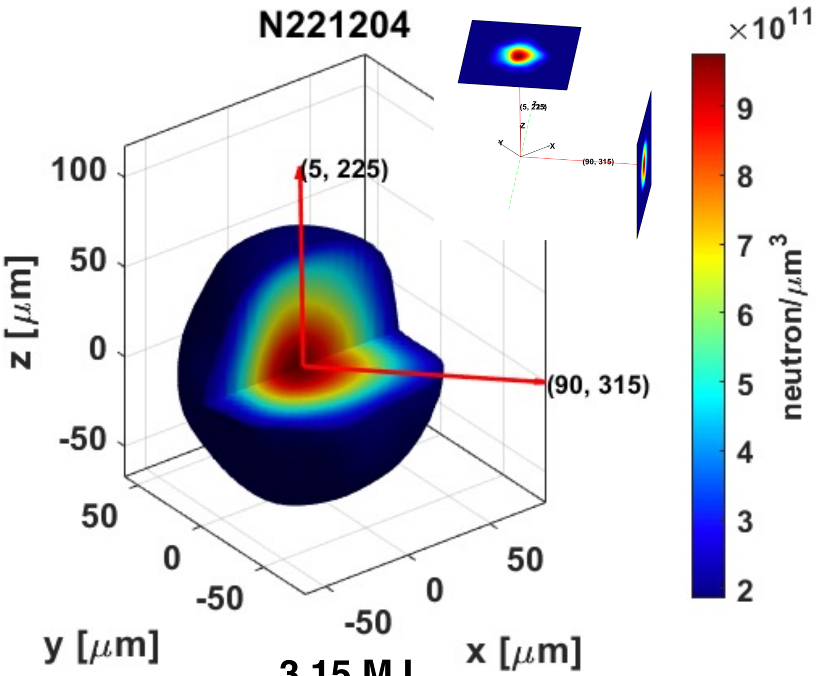
[1] Zylstra, et al., Nature, (2022); Kritcher, et al., Nature Phys. (2022); [3] Ralph, et al. "Hohlraum Scans Project," APS-DPP (2021); [4] Kritcher, et al., PRE (2018); [5] Hurricane, et al. PoP, (2017)

8% thicker ablator (m_{shell}), with +8% more laser energy, and improved symmetry pushed the 1.37 MJ result to 3.15 MJ

Time integrated neutron imaging



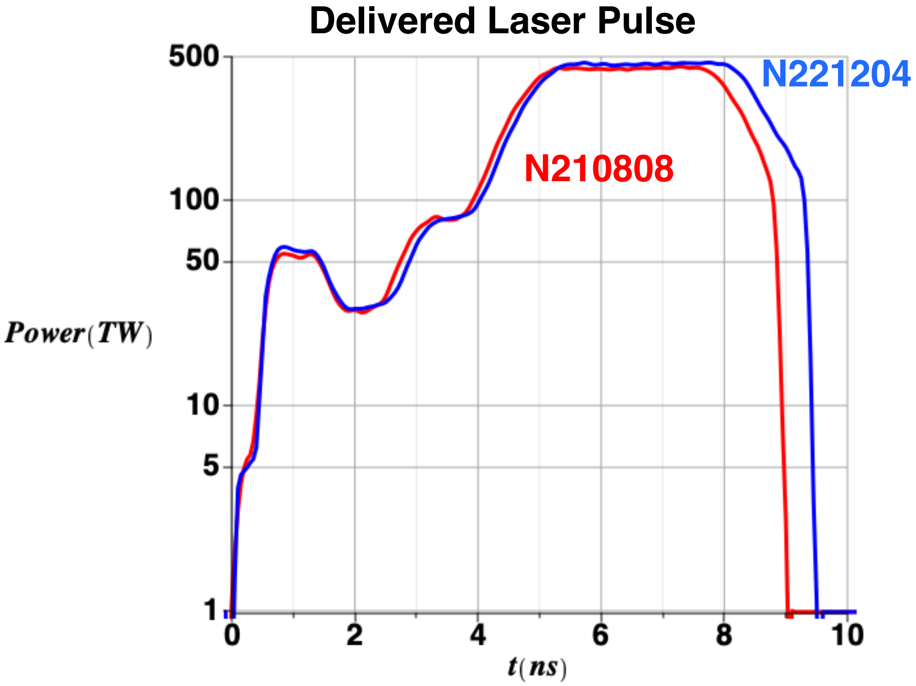
1.37 MJ

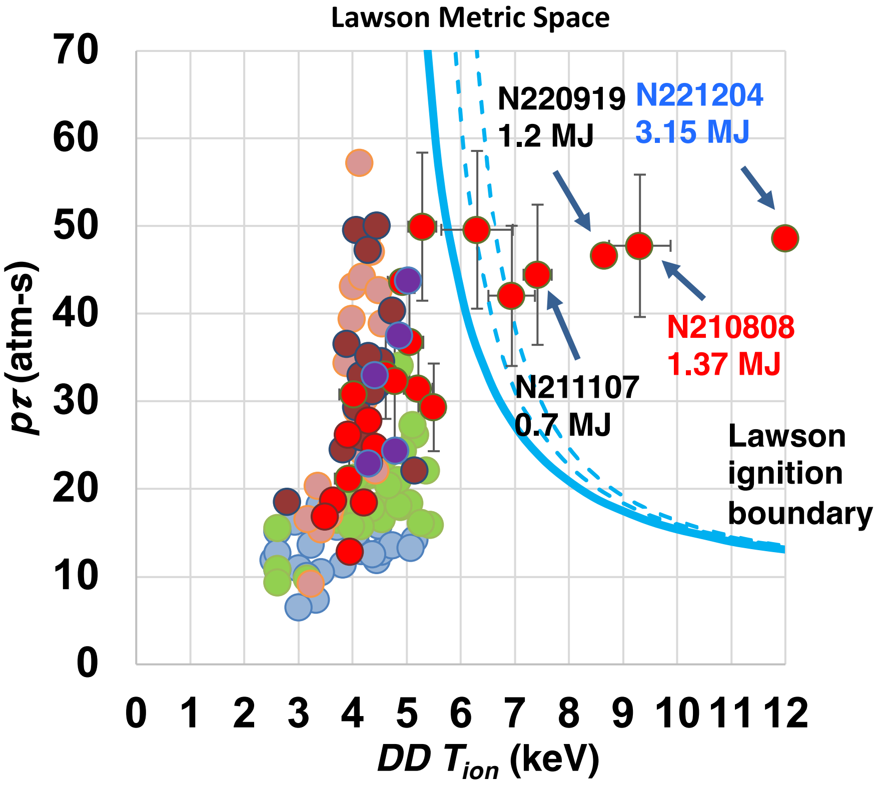


3.15 MJ

Neutron Imaging System; Vologev, et al., RSI, (2014)

Increasing laser energy and capsule thickness by +8%,while maintaining symmetry control, obtained G_{target} > 1 Dec. 5, 2022





Story of success by "incremental" evolutionary improvements

Outstanding problem: materials appear stiffer than models expected and higher compression is needed for increased burn efficiency

Measured compression

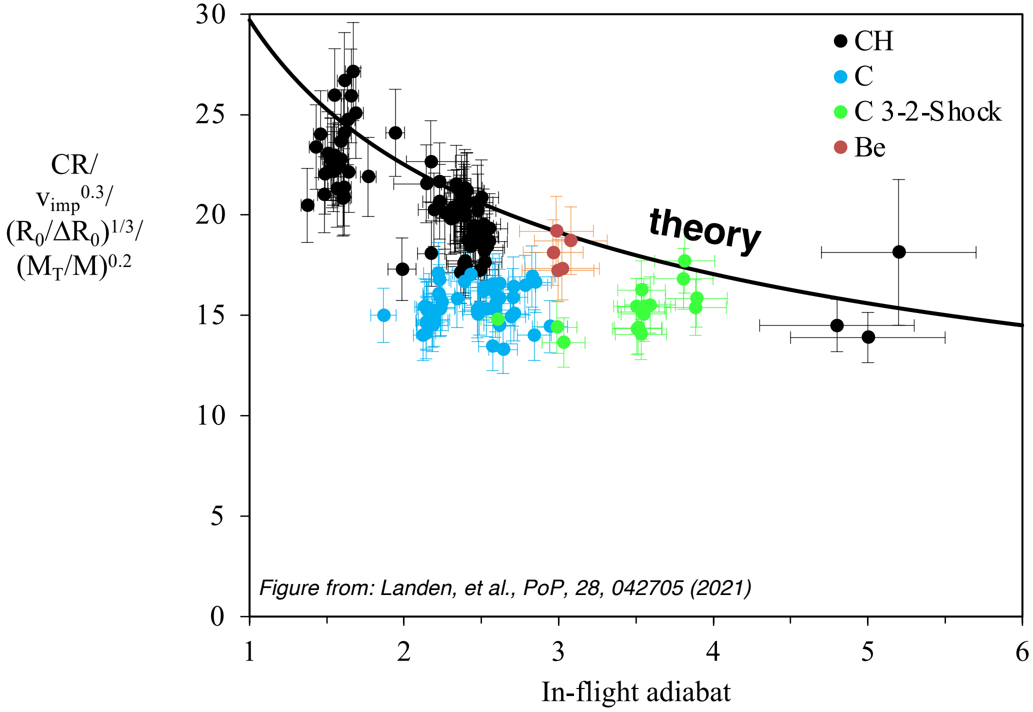


Figure from: Landen, et al., PoP, 28, 042705 (2021)

Expected compressibility based on entropy

Fraction of DT fuel burned:

$$\phi \approx \frac{\rho R_{fuel}}{\rho R_{fuel} + 7}$$

Fraley, et al., Phys. Fluids, 17, 1974

The end of the beginning…there is more work to do!

Remarkable that we can now talk about burning plasmas, ignition, and scientific breakeven ($G_{target} > 1$) in the past-tense!

- No mystery physics obstacle stands in the way of ignition (explosive thermodynamic instability) or gain (energy out > energy in)
- The theoretical prediction of the physics parameter regime (e.g. Lawson triple product) where ignition was expected consistent with our results
- Additional laser energy (at fixed power) was very beneficial
- Implosion physics was more sensitive to engineering control of the laser and targets than originally thought
- So far, very high gain (high compression) target designs have not worked as expected. All break-throughs over the past decade have used low gain designs

Lawrence Livermore
National Laboratory