US program in laser fusion

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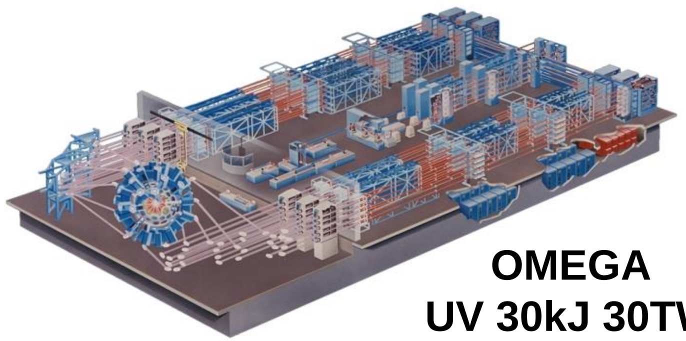
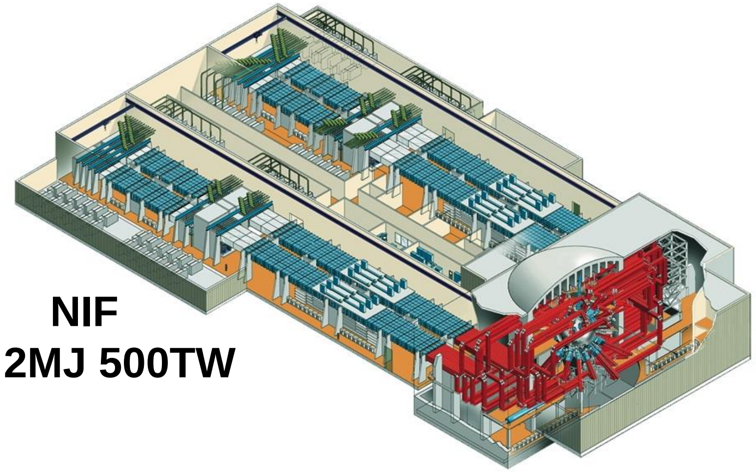
ELI Laser induced fusion: kick off meeting
ELI
Prague, Czech Republic, November 28-29, 2023

In the US, laser fusion is pursued through the direct and indirect drive approaches

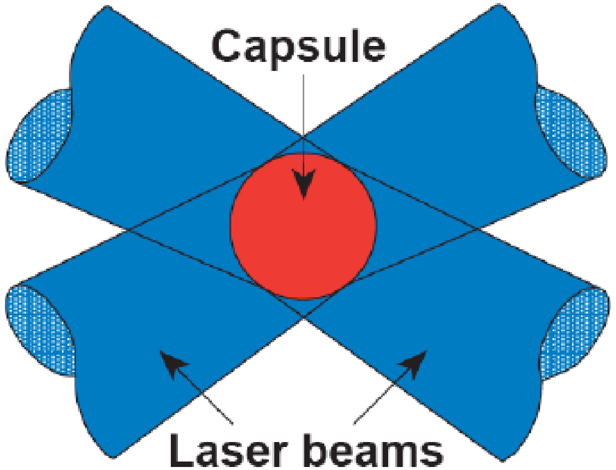


OMEGA
UV 30kJ 30TW

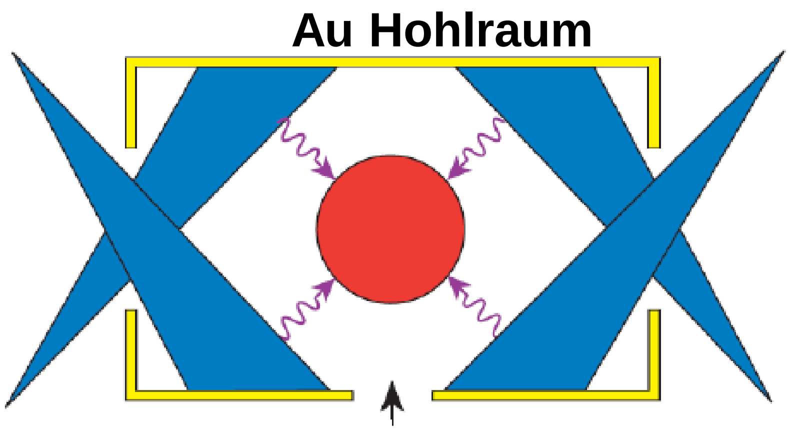


NIF
UV 2MJ 500TW

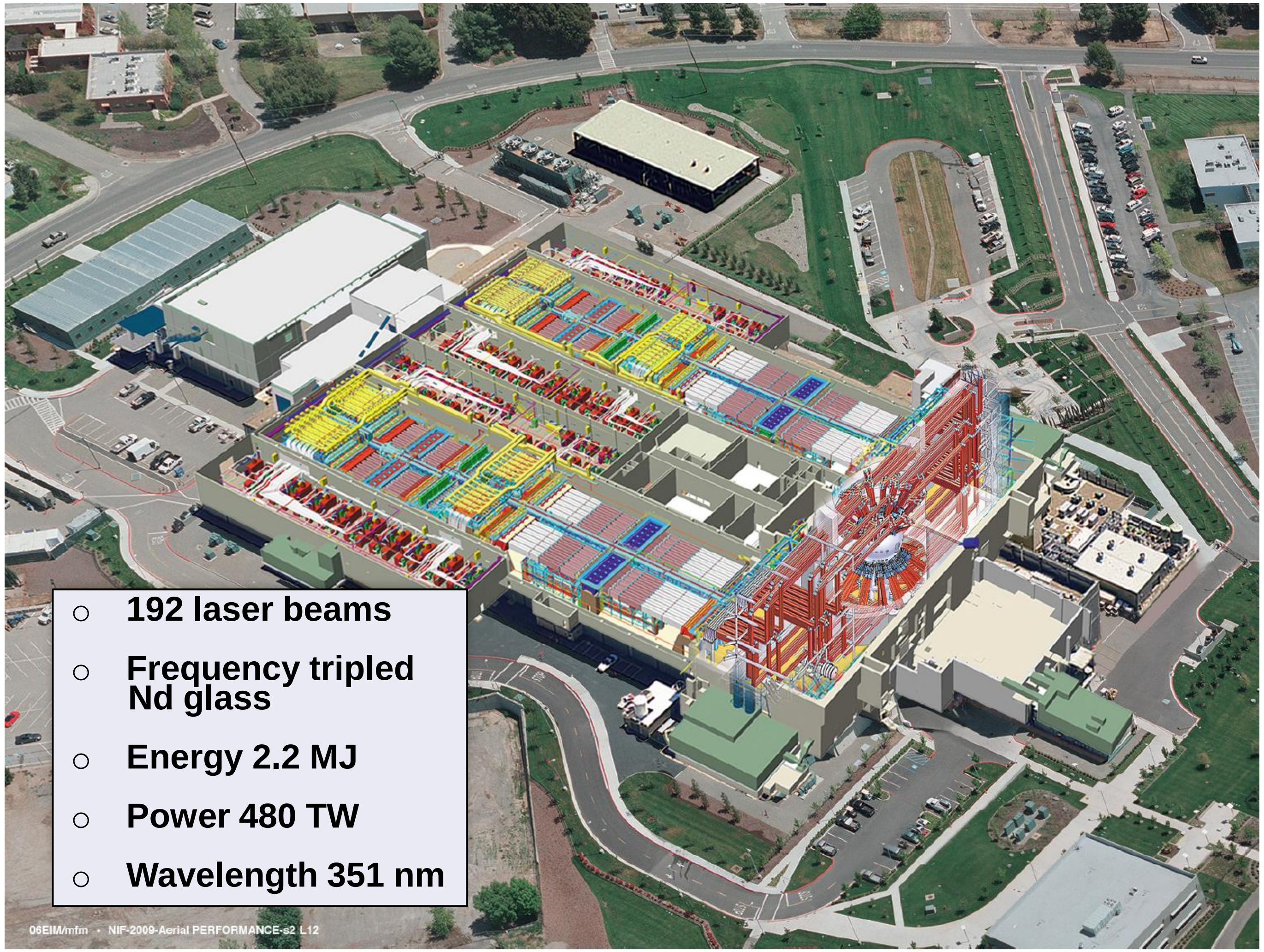
Direct-drive target



Indirect-drive target



The National Ignition Facility (NIF) at LLNL is the premier laser fusion facility in the US for indirect drive ICF



- 192 laser beams
- Frequency tripled Nd glass
- Energy 2.2 MJ
- Power 480 TW
- Wavelength 351 nm

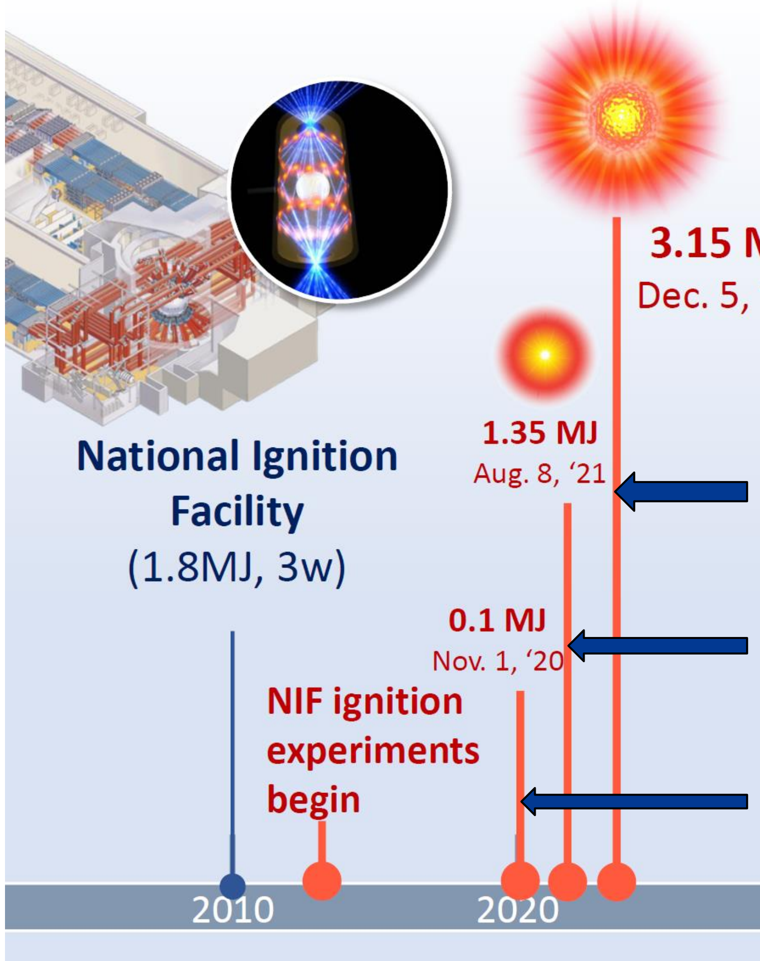
NIF construction started in 1997
NIF was commissioned in 2009
Up to 1 DT layered implosion per week
First burning plasma in 2020
First ignition in 2021
First Target Gain > 1 in 2022

Within two years, NIF implosions advanced from burning plasmas (2020) to thermonuclear ignition and energy gain (2021-2022)

Normalized Lawson parameter

$$\chi = \frac{P\tau}{(P\tau)_{ign}}$$

$$Q_\alpha = \frac{E_\alpha}{W_{pdV}}$$



Target Gain > 1
$\chi > 1$, $Q_\alpha \approx$ 55-65

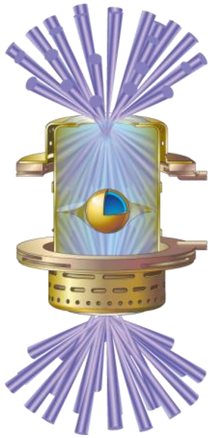
Ignition by the Lawson criterion
$\chi \approx 1$, $Q_\alpha \approx$ 20-30

Burning plasmas
$\chi \approx 0.8$, $Q_\alpha \approx$ 1-2

Highest Target Gain 1.9x

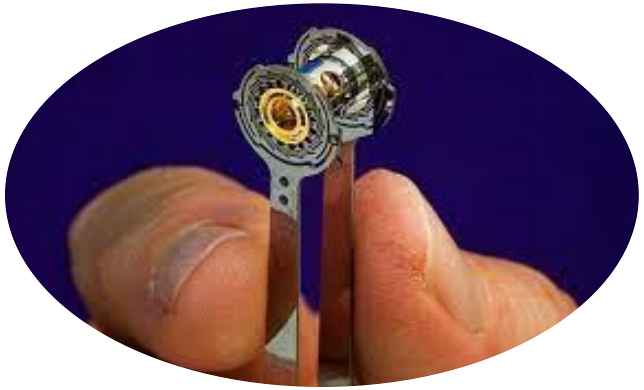
Fusion Energy > Laser Energy on Target

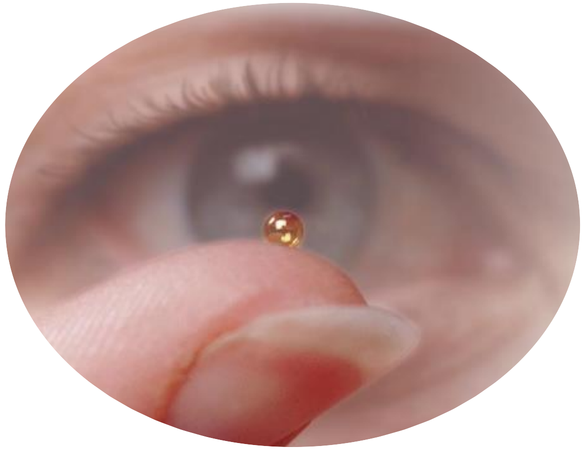
2.05 MJ of laser energy IN

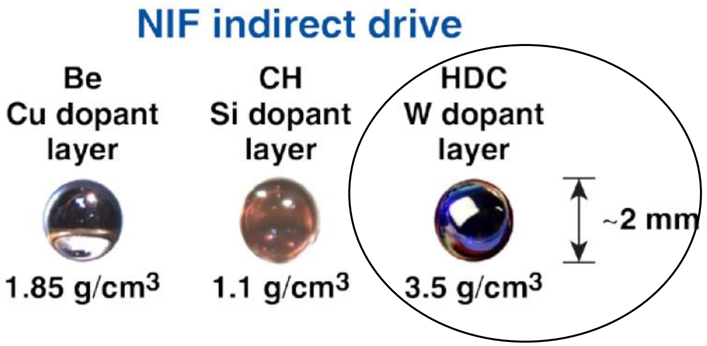


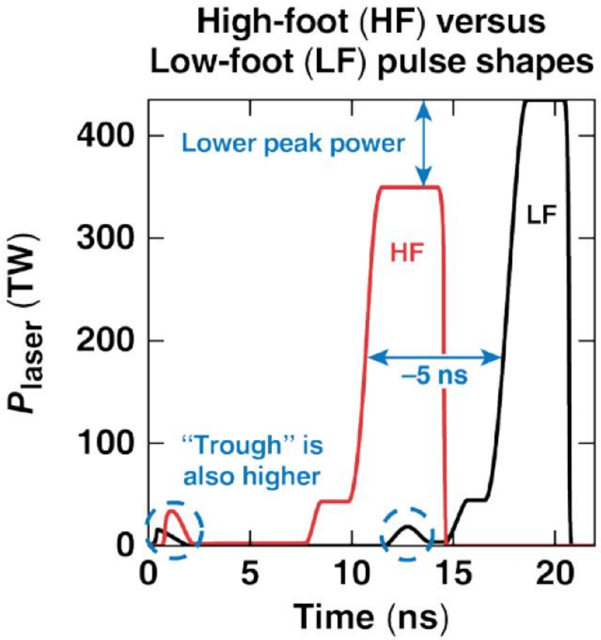
3.9 MJ of laser energy OUT

The design of targets and laser pulses has evolved to make implosions more stable and more tolerant to mix



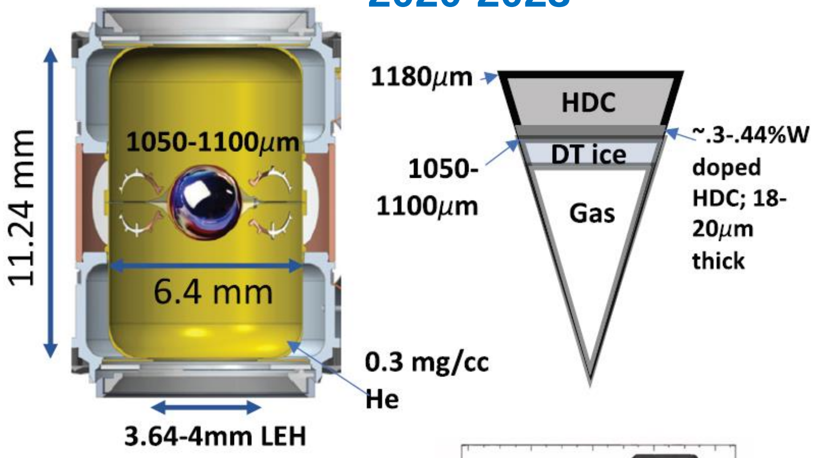


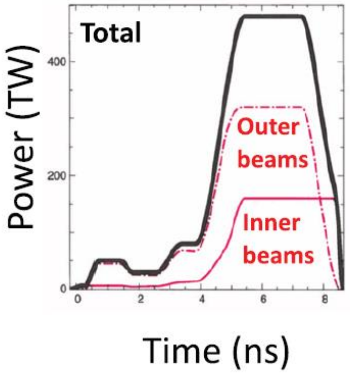




← *Pulse shapes used in CH target
Hurricane et al, Nature 2014

Hybrid-E targets & pulse shapes 2020-2023

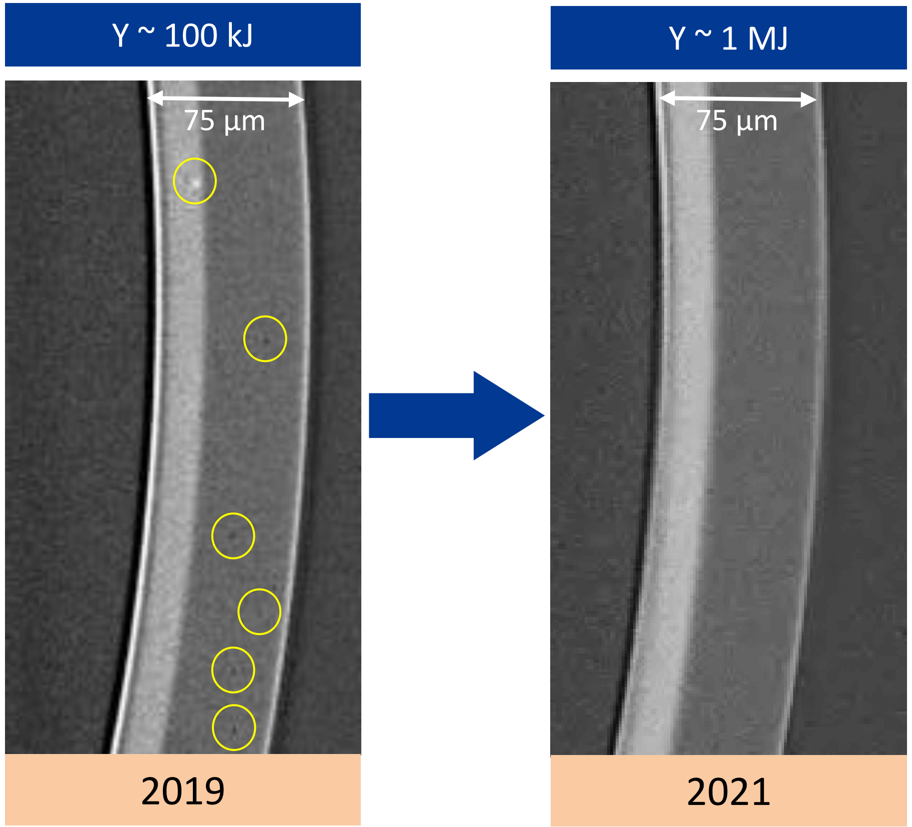




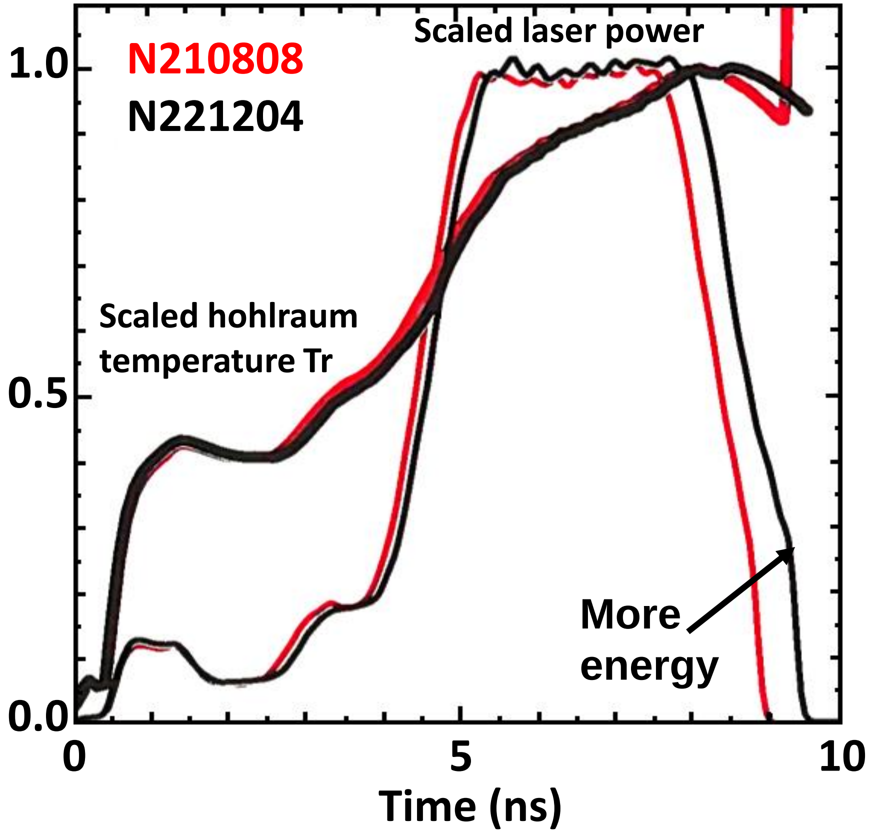
Kritcher et al, Phys. Plasmas (2021)
Zylstra et al, Phys. Rev. Lett. (2020)

Better quality capsules, more laser energy and target design adjustments were key in achieving ignition on the NIF

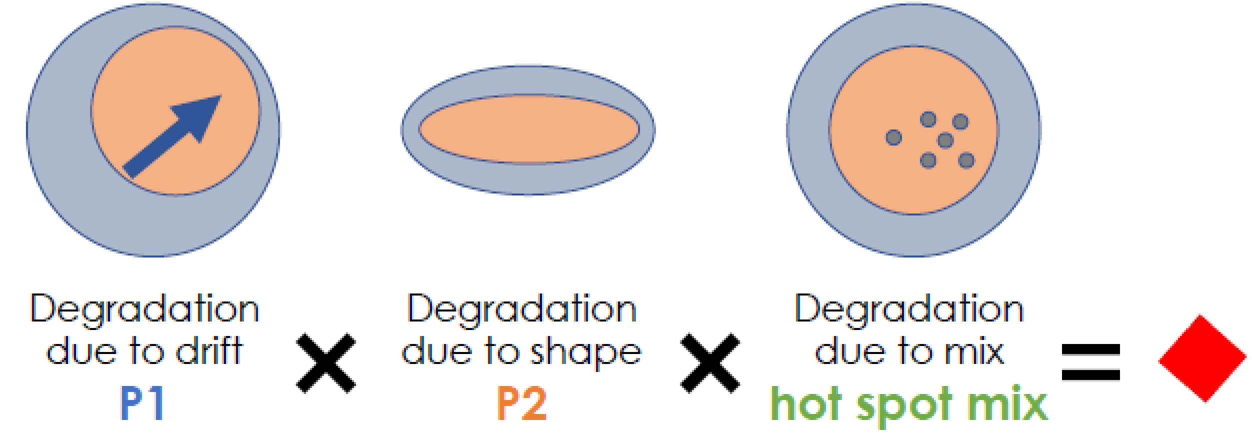
Better quality targets (fewer defects)



More laser energy from 1.9 to 2.05 MJ



Large variability in the fusion yield was observed in the repeats of shot 210808 (1.35 MJ yield)

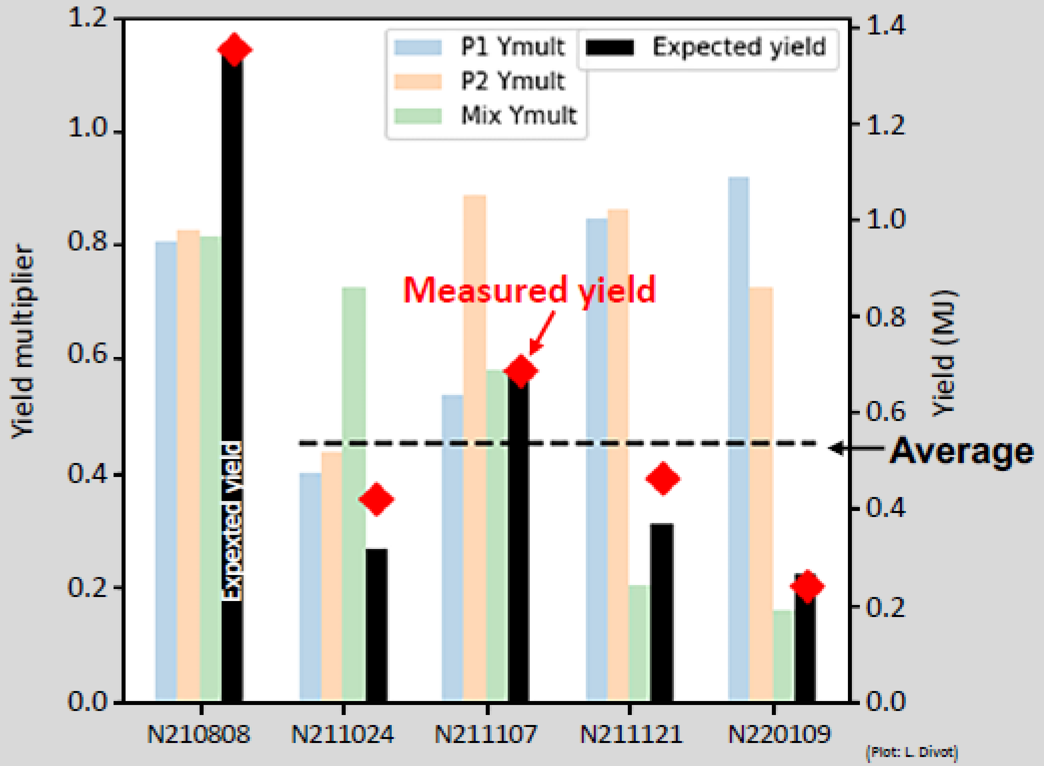


Repeats with:

With N210808 levels of mix: <**1.1**MJ> ± 0.3

With observed levels of mix: <**0.5** MJ> ± 0.2

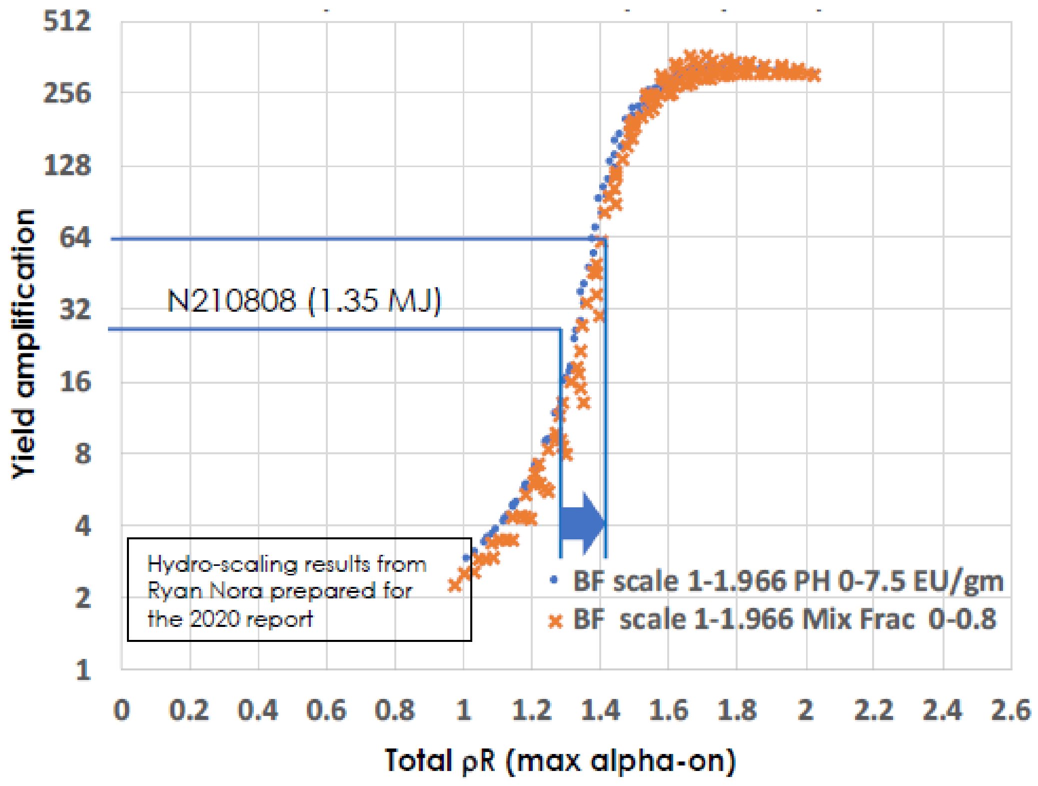
Yield variation for repeat experiments



Mix was the dominant nuclear yield degradation mechanisms in the 1.35MJ repeats

Large variability in yield suggests that current NIF implosions are operating on the ignition cliff. If true, higher yields are possible on current NIF

Current designs are operating in a regime where small increases in confinement can lead to large increases in yield amplification from alpha heating



Higher yield could be achieved through:

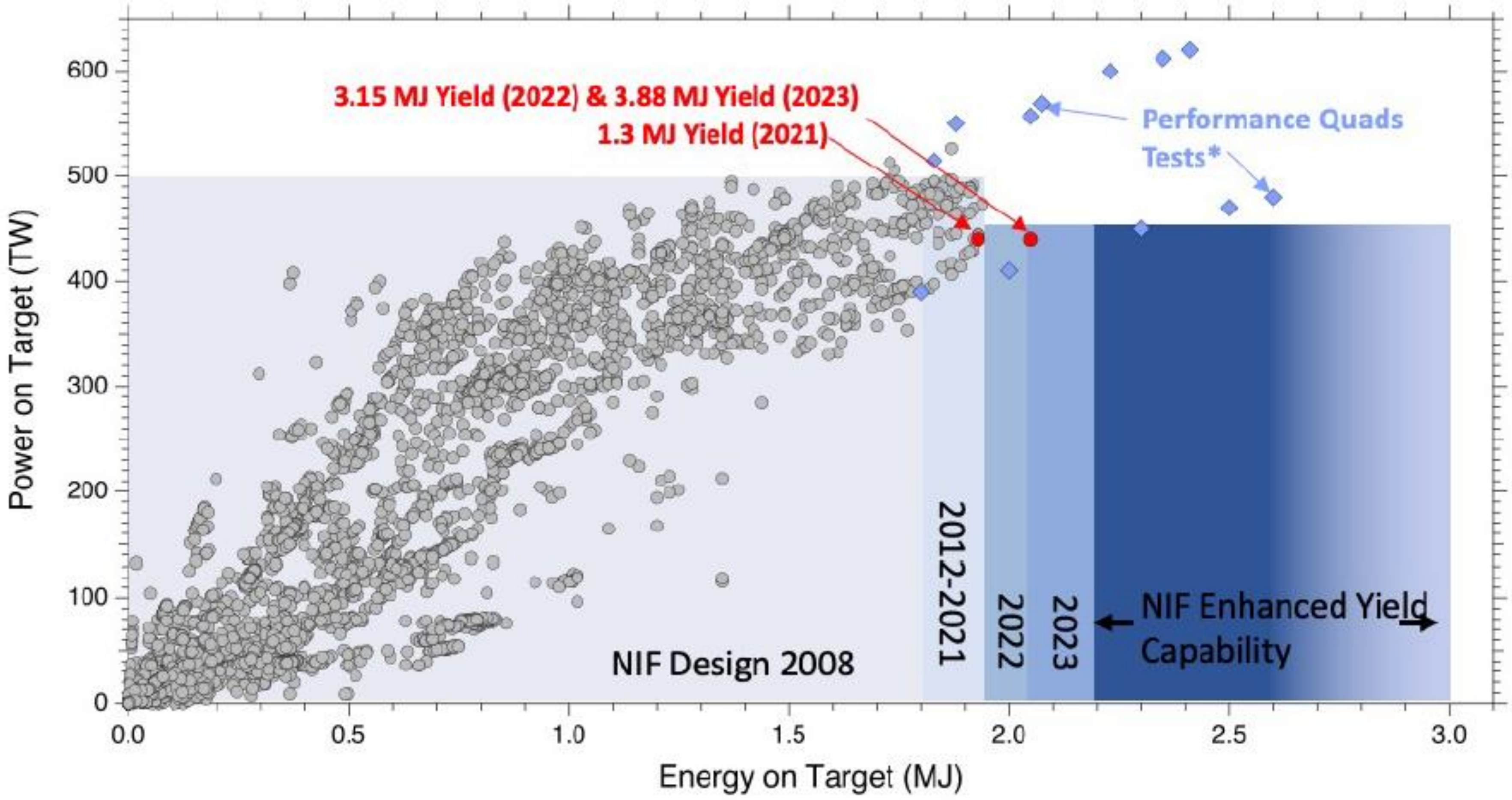
- Higher compression designs
  - Adjust shock timing
- More stable designs
  - SQ-n drive: First shock followed by a compression wave

  R. Tomassini et al, IFSA conference 2023
- Couple more energy to the hotspot
  - Higher efficiency hohlraums

    C. Young et al, IFSA conference 2023
  - Increased laser energy

    A. Kritcher et al, IFSA conference 2023

Performance tests are planned to confirm the viability of power and energy upgrades (600TW / 3MJ) of the NIF

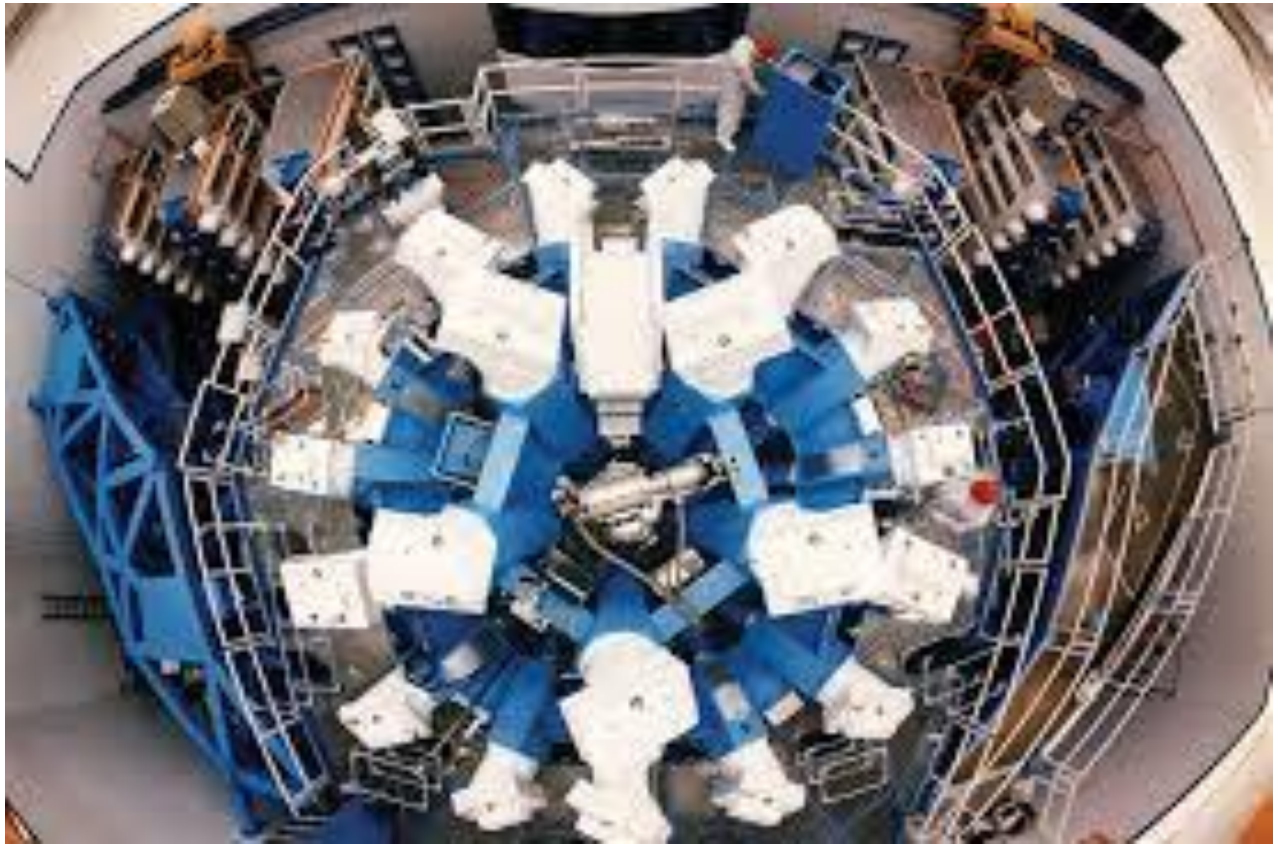


Initial target designs for NIF upgrade indicate the possibility to achieve up to 30MJ yields

Questions on whether a powerful laser can ignite thermonuclear fuel in the laboratory have been put to rest

- ❑ For the first time a fusion plasma was ignited in the laboratory
- ❑ What comes next for indirect-drive implosions on NIF?
- ❑ Robust and repeatable ignition
- ❑ Higher energy gains with existing NIF (if current ignition still on cliff)
- ❑ 3MJ upgrade of NIF with projected yields up to ~ 30 MJ

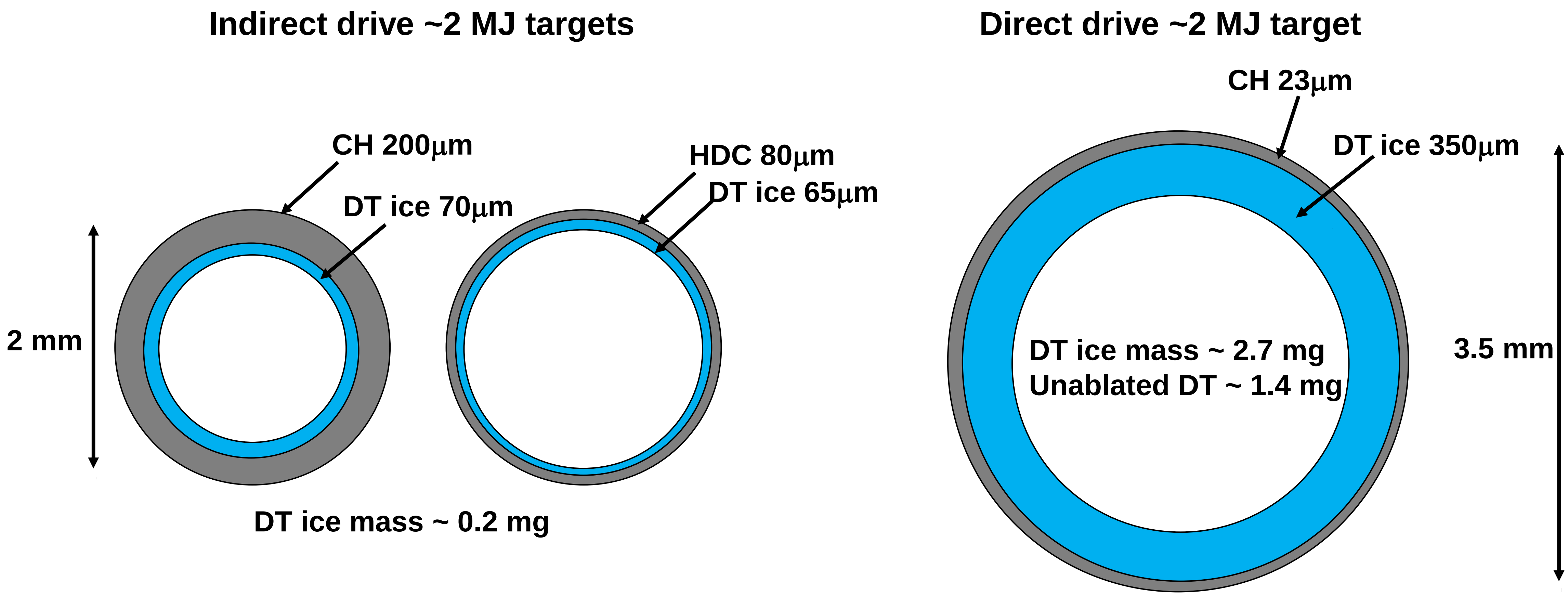
Direct-drive DT-layered implosion experiments are carried out on the OMEGA laser at the UR Laboratory for Laser Energetics (LLE)



- 60 laser beams
- Frequency tripled
- Energy 30 kJ
- Power 30 TW
- Wavelength 351 nm
- Up to 5 DT layered implosions per month
- Commissioned in 1995

LLE is also pursuing direct-drive (polar) experiments on the NIF using surrogate plastic shells and planar foils to study laser-plasma interactions at ignition scale

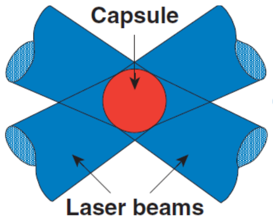
For the same laser energy, direct drive capsules are bigger and store more fuel than indirect drive



In indirect drive, about 5% of the ablator mass remains. The remaining ablator mass is approximately the same as the DT ice mass. In direct drive, all the ablator material and about 50% of the DT ice are ablated off.

Direct drive couples ~ 3x more energy to the capsule and can drive up to ~6x the fuel mass of indirect drive, an attractive path for high energy gains

UR LLE



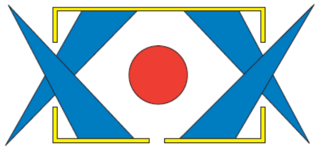
OMEGA Direct Drive

Laser Energy ≈ 28.5 kJ

Shell Kinetic Energy (all fuel) ≈ 1.5 kJ

Efficiency ≈ 5.2%

NIF Indirect Drive



Laser Energy ≈ 2.05 MJ

Shell Kinetic Energy ≈ 15(fuel)+15(HDC[1]) = 30 kJ

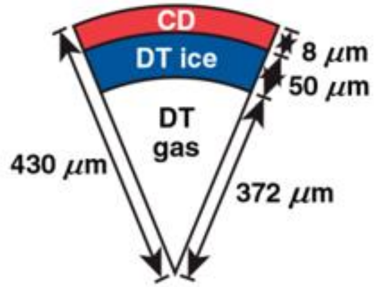
Efficiency ≈ 1.4%   HDC Mass ≈ Fuel Mass

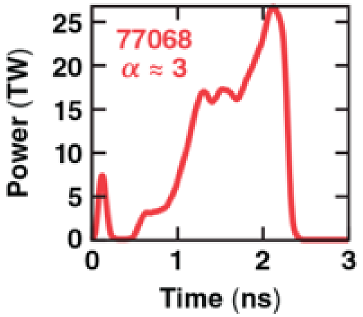
- To date, implosion quality (convergence and compressibility) has been higher for indirect drive on NIF with respect to direct drive on OMEGA.
- Improving the quality of direct drive implosions is a high priority of the OMEGA laser fusion program

Direct drive has the potential for energy gains greater than Indirect Drive (up to 6x)

[1] HDC = High Density Carbon
[2] A. Davis et al, Phys. Plasmas 23, 056306 (2016)
[3] LPI = laser-plasma interactions/instabilities

OMEGA target designs are guided by the predictions from a data-driven statistical model (SM)[1-4]





Simulation

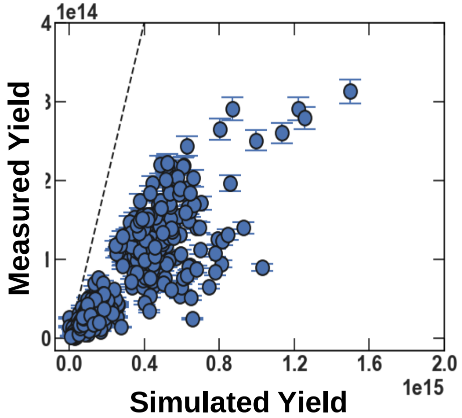
Simulation Outputs

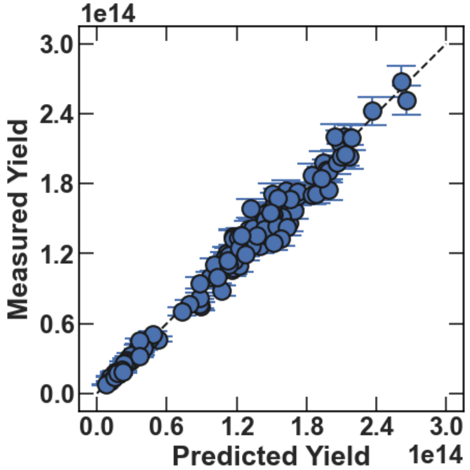
f_{map}

Model trained over ~ 300 OMEGA shots using PNL[5], DNN[6]

Experiment

Measurements





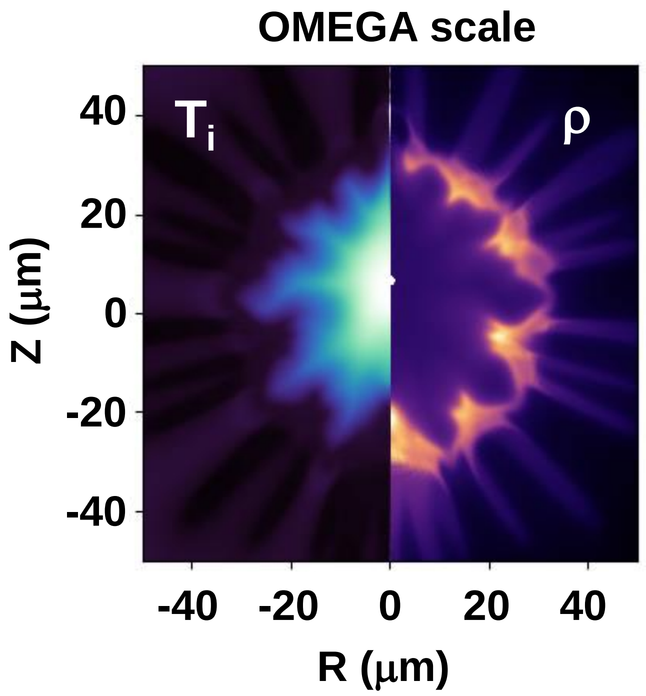
The model is accurate across a wide range of adiabats, convergence ratios, velocities and intensities

[1] V. Gopalaswamy et al, Nature 565, 581-586 (2019)
[2] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021)
[3] V. Gopalaswamy et al, Phys. Plasmas 28, 122705 (2021)
[4] A. Lees et al, PoP (2023)

[5] PNL = Piecewise Nonlinear Regression
[6] DNN = Deep Neural Networks

With 30kJ of laser energy, OMEGA cannot access ignition. The performance of direct-drive implosions is extrapolated to larger sizes/energies using simulations

Simulated reconstruction of OMEGA experiment (reproduces observables)

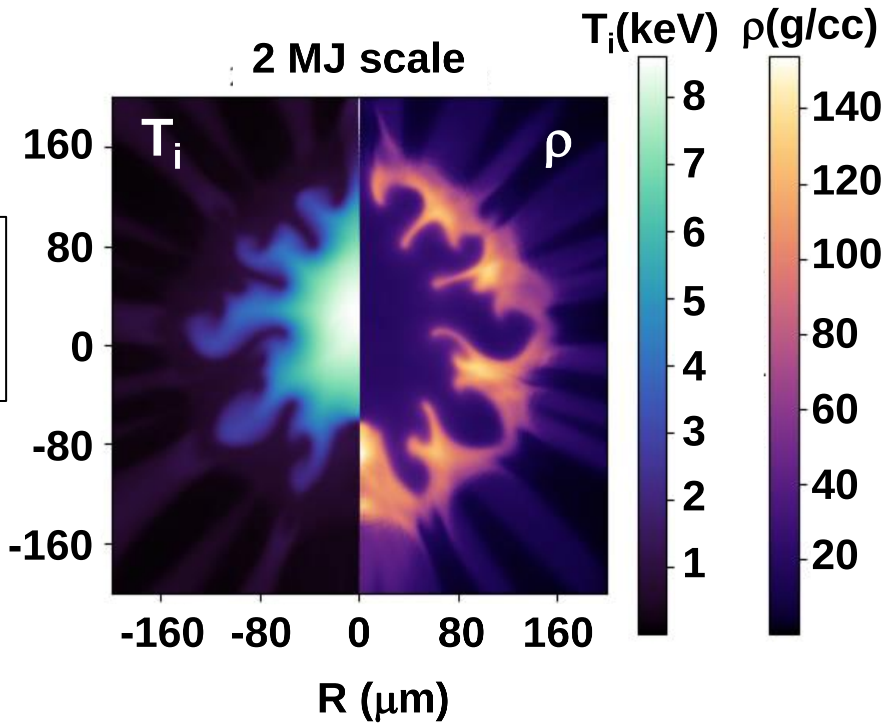


Hydrodynamic scaling

$$R \sim E_L^{1/3} \Rightarrow$$

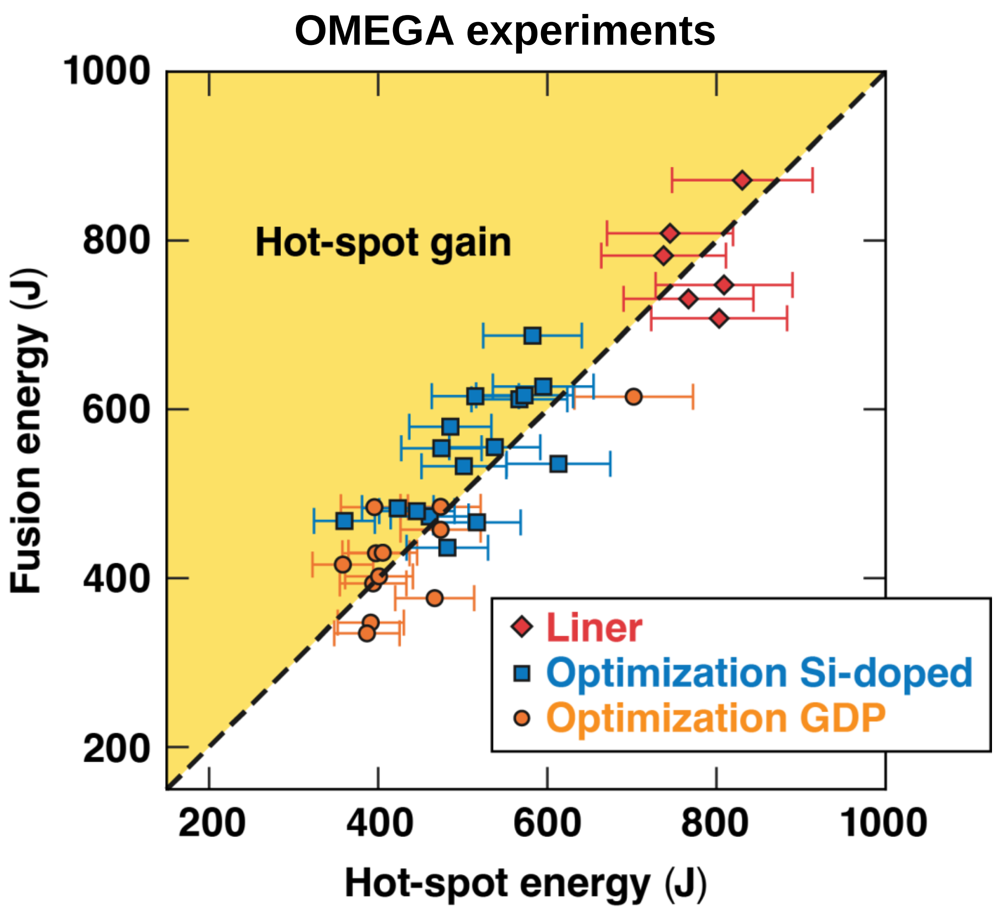
$$R_{2\,MJ} \approx 4.1 \times R_{OMEGA} \Rightarrow$$

Hydro-scaled simulation

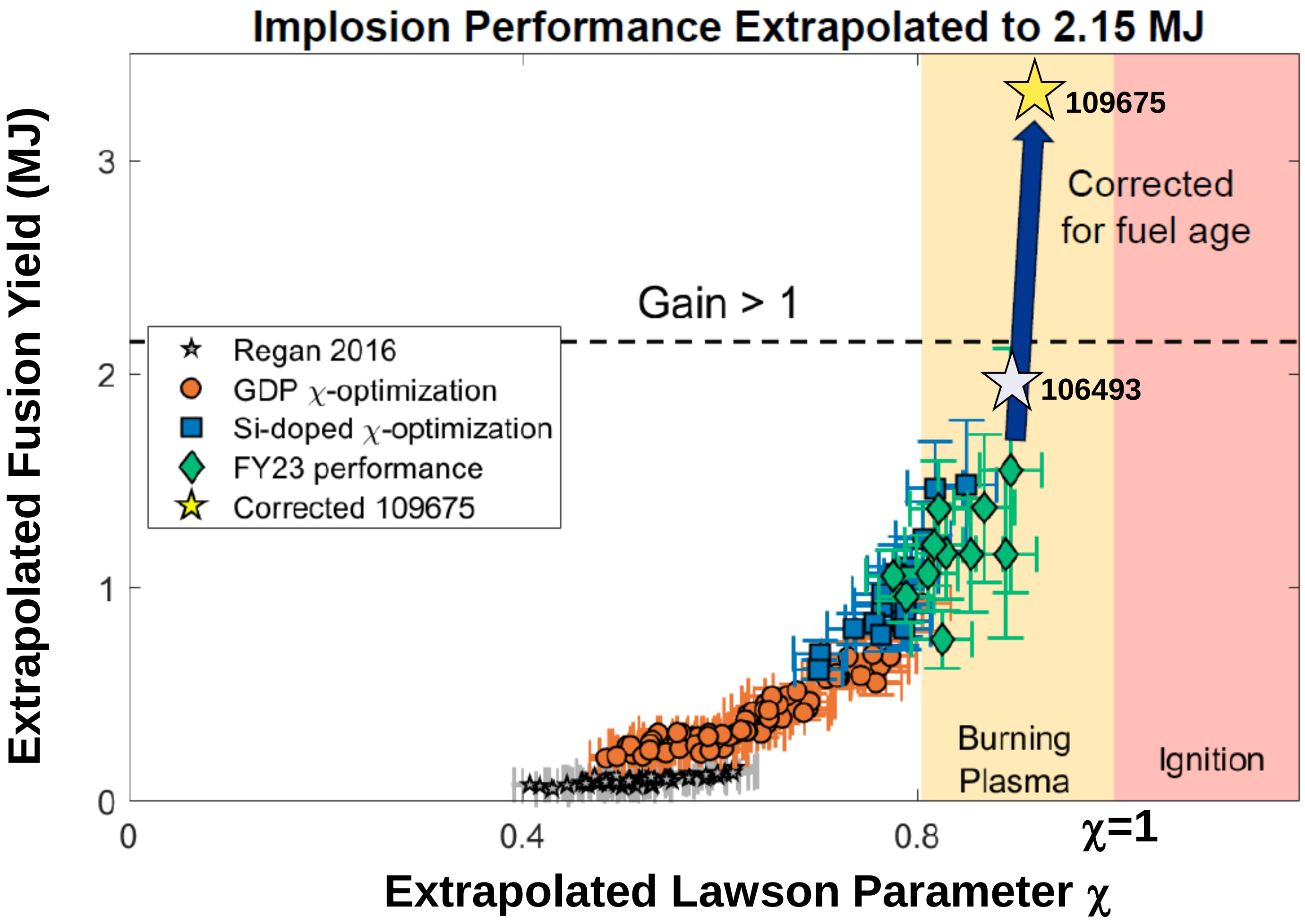


[1] V. Gopalaswamy et al, accepted in Nature Physics

The extrapolated performance of OMEGA direct-drive implosions is close to the ignition threshold (90% of the Lawson parameter required for ignition)



TC16273



Future plans include multiple options to improve implosion performance including fundamentally new designs and new laser technologies

- ❑ Subcooling below the triple point
- ❑ Real-time shock-timing optimization

Performance improvements of existing designs

- ❑ Hybrid-Shock-Drive[1-3]
- ❑ Shock-Augmented-Ignition[4]

New designs

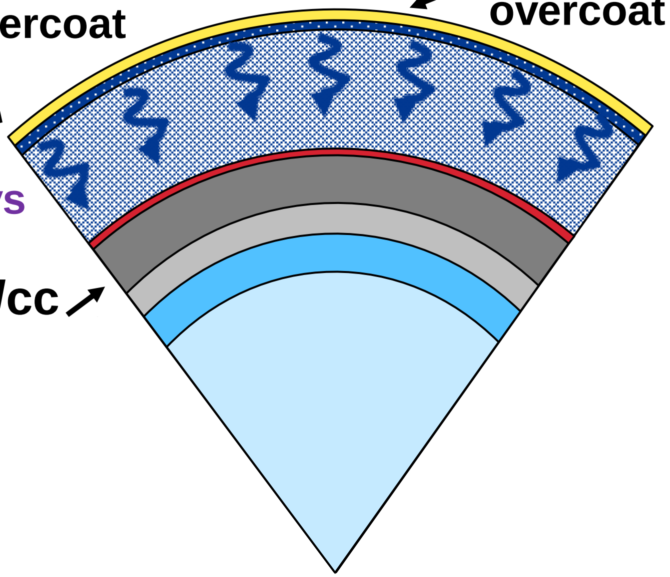
- ❑ Broadband lasers (FLUX)

New laser architecture

[1] L. Ceurvorst et al, Phys. Rev. E 101, 063207 (2020)
[2] P. Farmakis et al (IFSA 2023)
[3] M. Karasik et al, Phys. Rev. Lett. 114, 085001 (2015)
[4] R. Scott et al, Phys. Rev. Lett. (2023)

Hybrid shock drive uses a strong picket in the laser pulse shape to drive a smooth first shock using x-rays

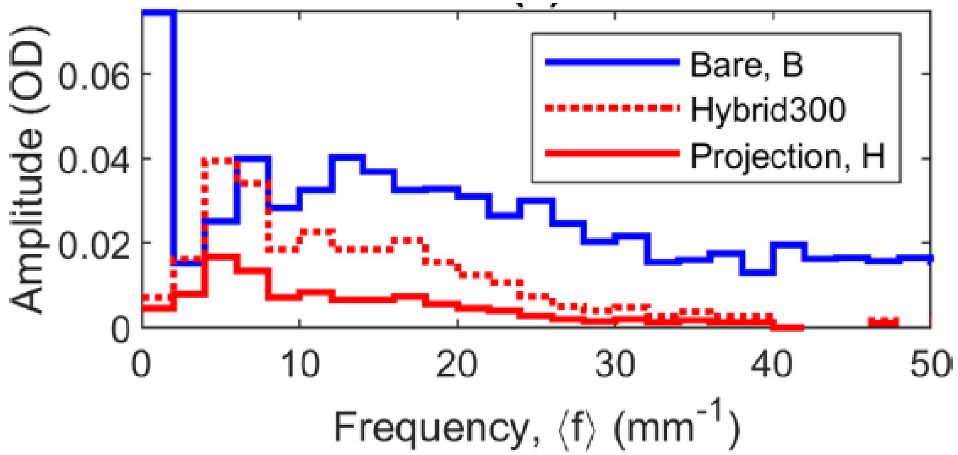
Spherical Hybrid Shock Target[2]



Comparison of 1D design performance [2]

	Design	ρR (mg/cm²)	Yield (1e14)	Adiabat
Current best performer →	104949 (peak 27 TW)	185	5.58	5.2
Hybrid Shock Drive →	fHSD (peak 25 TW)	320	12.7	~2

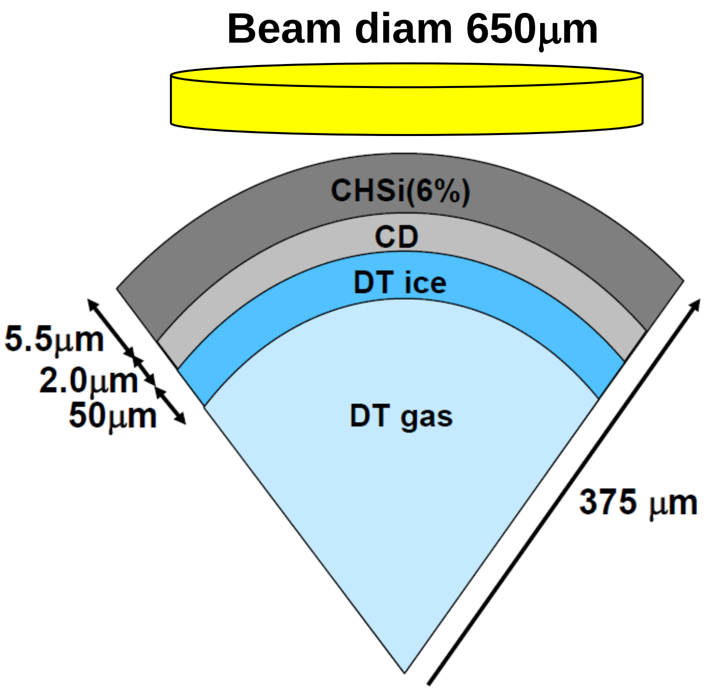
Planar experiments[1] : Imprinting spectrum



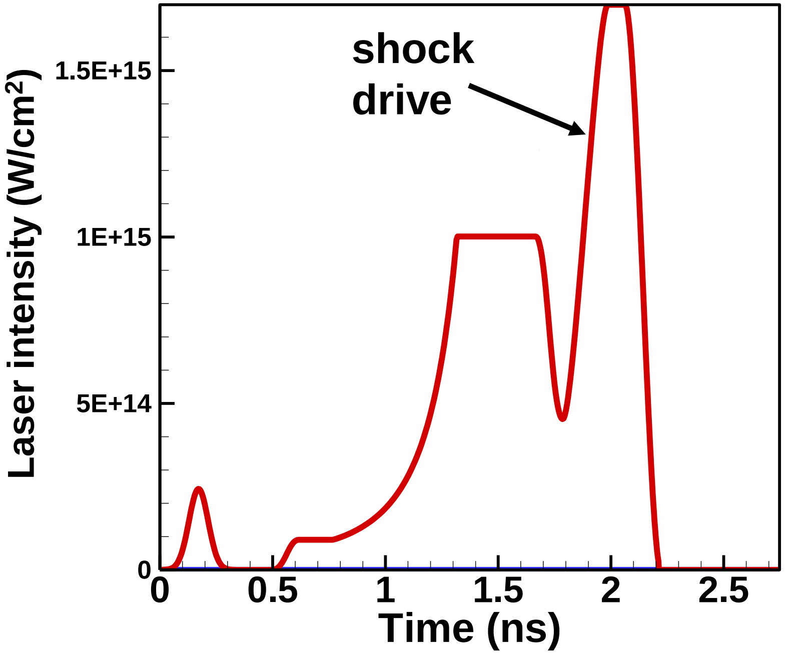
Hybrid-Shock-Drive can mitigate laser imprinting and enable low-α direct-drive implosions.[1-3] Warm implosions scheduled for FY24 on OMEGA

[1] L. Ceurvorst et al, Phys. Rev. E 101, 063207 (2020)
[2] P. Farmakis et al (IFSA 2023)
[3] M. Karasik et al, Phys. Rev. Lett. 114, 085001 (2015)

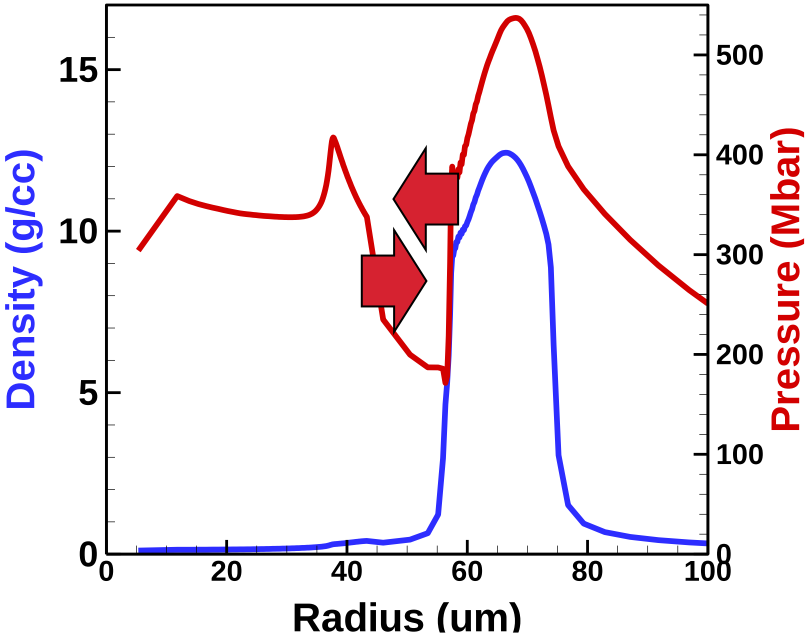
Shock augmented ignition is being tested on OMEGA using smaller targets and laser beam sizes to achieve highest intensities for ignitor shock launch



Laser intensity vs time



Density and pressure at time of shock collision



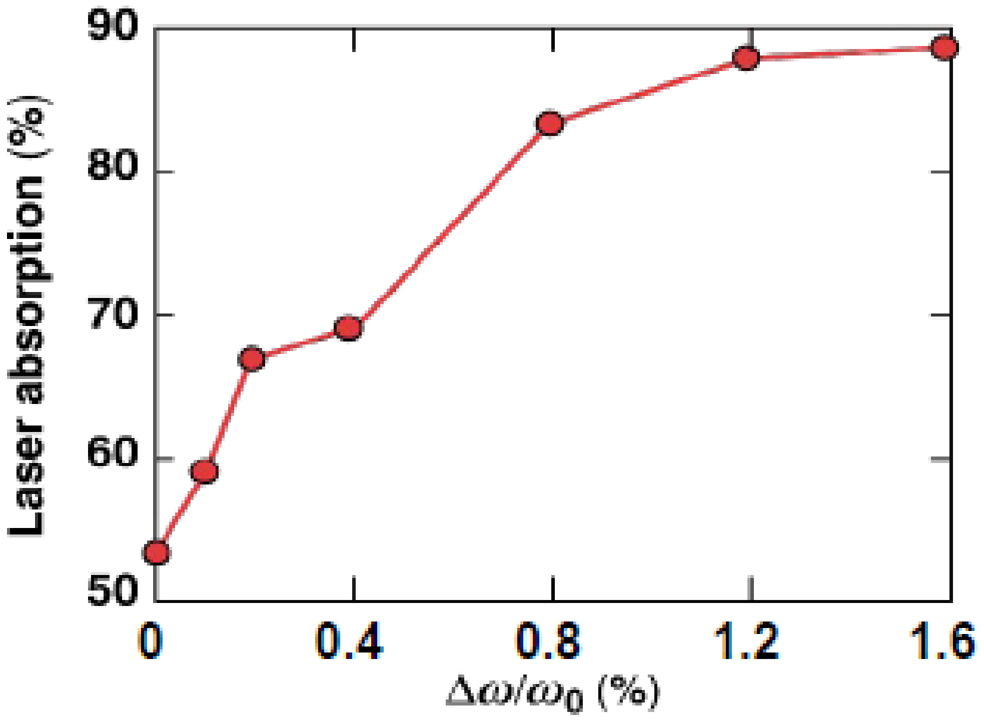
Ignition shock pressures are well below standard shock-ignition[3] requirements

Preliminary results from last week initial experiments indicate good performance relative to past implosions with similar ice thickness

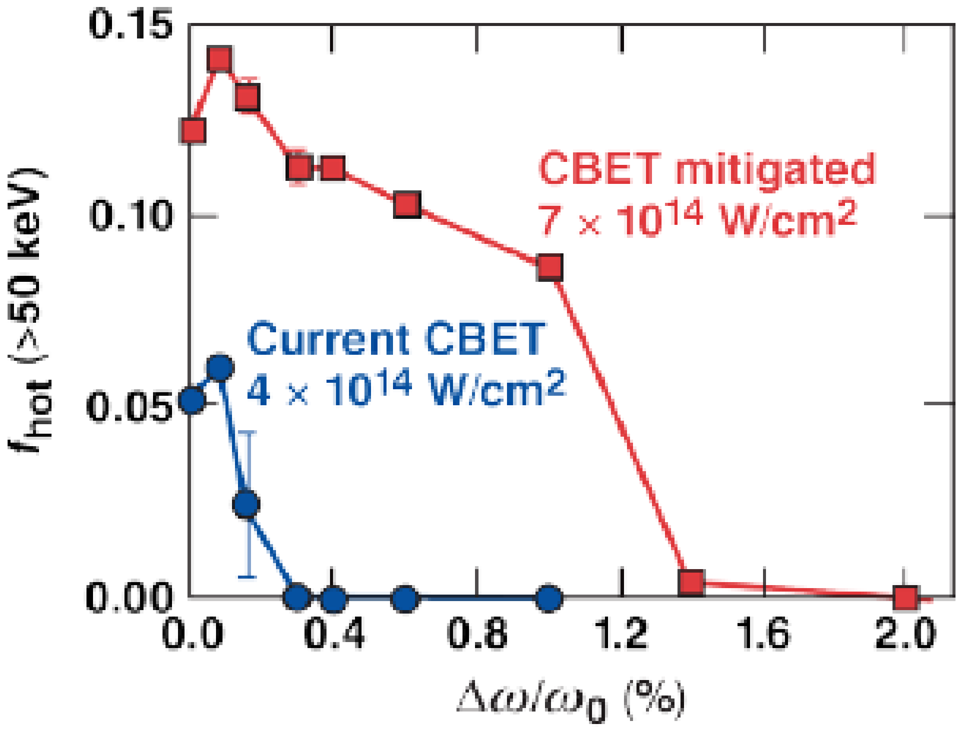
[1] R. Scott et al, Phys. Rev. Lett. 129, 195001 (2021)
[2] Designs by A. Lees (LLE)
[3] R. Betti st al, Phys. Rev. Lett. 98, 155001 (2007)

Higher performance can be achieved with greater laser bandwidth which improves energetics by suppressing laser-plasma instabilities

Bandwidth suppression of CBET and increase in laser energy absorption[1]



Suppression of hot electrons from LPI before and after CBET mitigation[2]

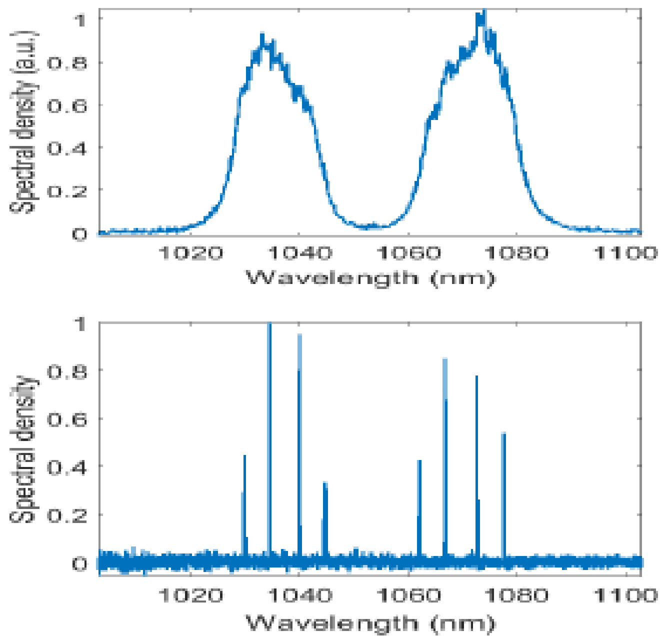


CBET = Cross Beam Energy Transfer (reduces laser absorption)

[1] R. Follet et al, Phys. Rev. Lett. 120, 135005 (2018)
[2] R. Follet al, Phys. Plasmas 28, 032103 (2021)

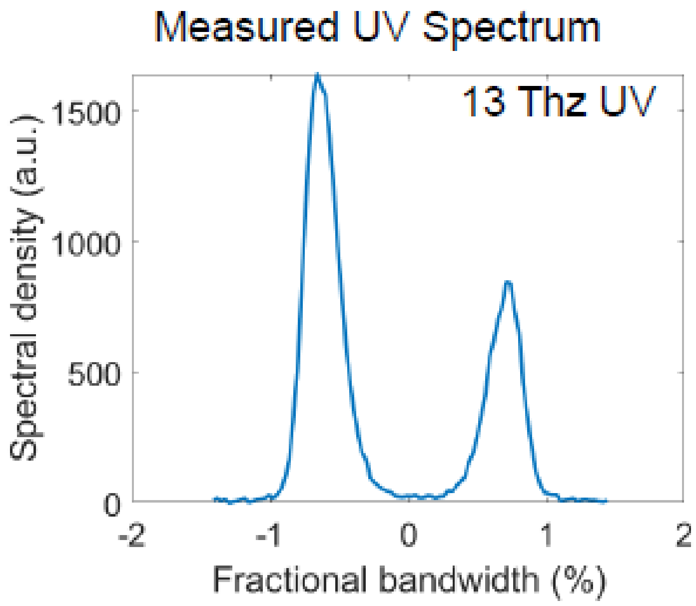
The Fourth generation Laser for Ultrabroadband eXperiments (FLUX) is under construction and will use the OMEGA LPI Platform to validate bandwidth modeling

Ultrabroad Band Laser* (concept demonstration)



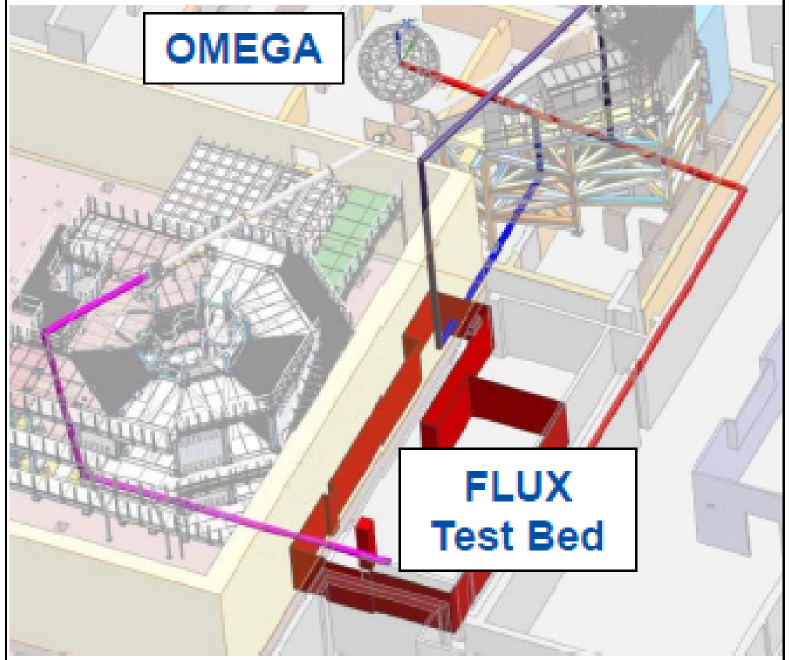
A colinear OPA was used to amplify broad bandwidth long-pulse laser beam

Demonstrated Broadband UV Frequency Conversion**



Novel concept demonstrates efficient broad band ($\Delta\omega/\omega$>1.5%) UV frequency tripling

The FLUX laser will feed the OMEGA LPI Platform



FLUX experiments will validate LPI modeling with bandwidth

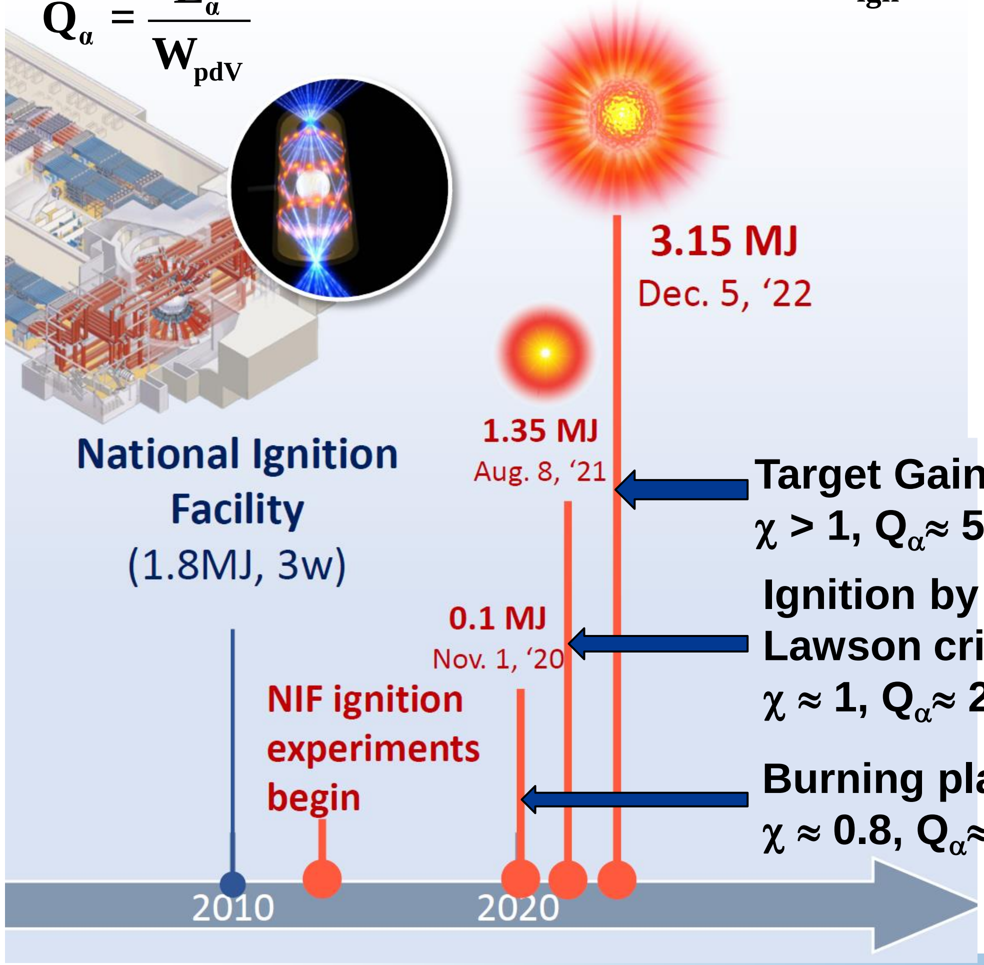
*C. Dorrer *et al.*, Opt. Express **28**, 451 (2020)
C. Dorrer *et al.*, Opt. Express **29, 16135 (2021)

conclusions

The physics principles of laser fusion have been demonstrated and both direct and indirect drive ICF are viable schemes for inertial fusion energy

Normalized Lawson parameter $\chi = \frac{P\tau}{(P\tau)_{ign}}$

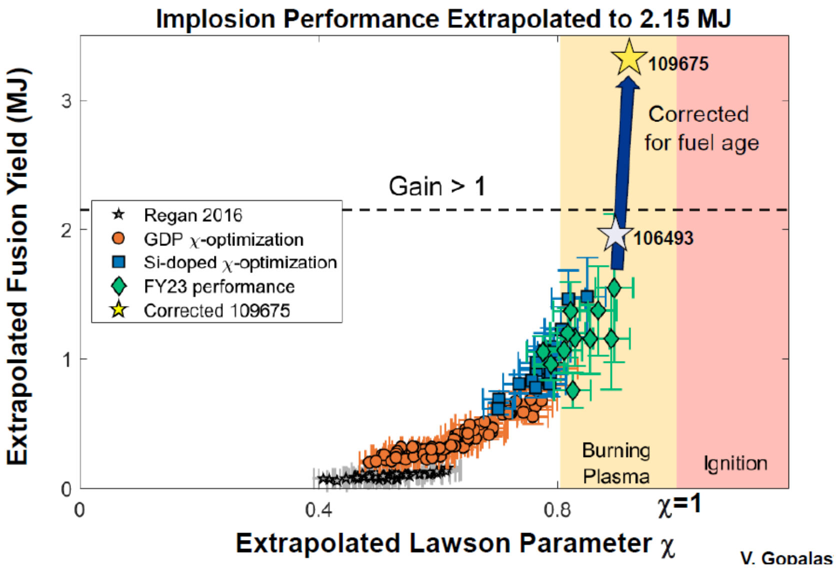
$$Q_\alpha = \frac{E_\alpha}{W_{pdV}}$$



Target Gain > 1
$\chi > 1$, $Q_\alpha \approx$ 55-65

Ignition by the Lawson criterion
$\chi \approx 1$, $Q_\alpha \approx$ 20-30

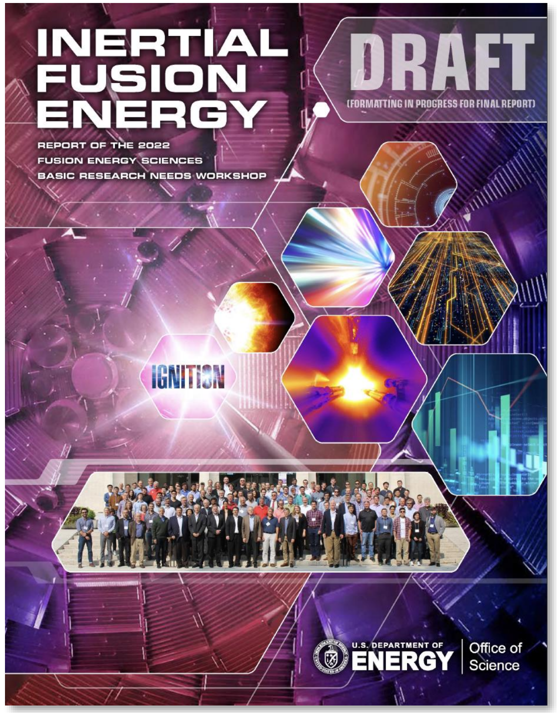
Burning plasmas
$\chi \approx 0.8$, $Q_\alpha \approx$ 1-2



Direct drive

Indirect drive

Inertial Fusion Energy



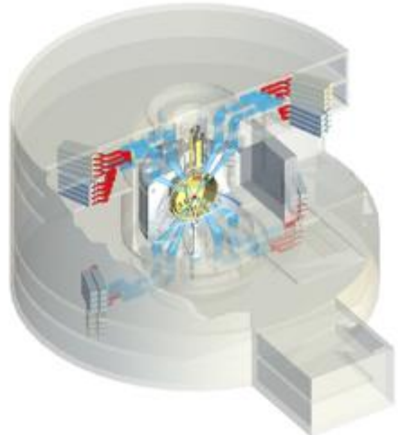
BACK UP

Fusion energy may be the ultimate clean and limitless energy source but many challenges remain

Desirable features for future energy sources

- Carbon-free
- Abundant and geographically diverse fuel
- Environmentally sustainable
- Passively safe
- Ability to meet baseload
- Can be generated near population centers
- Flexible energy products (electricity, process heat, H_2 and biofuels, H_2O production)
- Minimal proliferation concerns

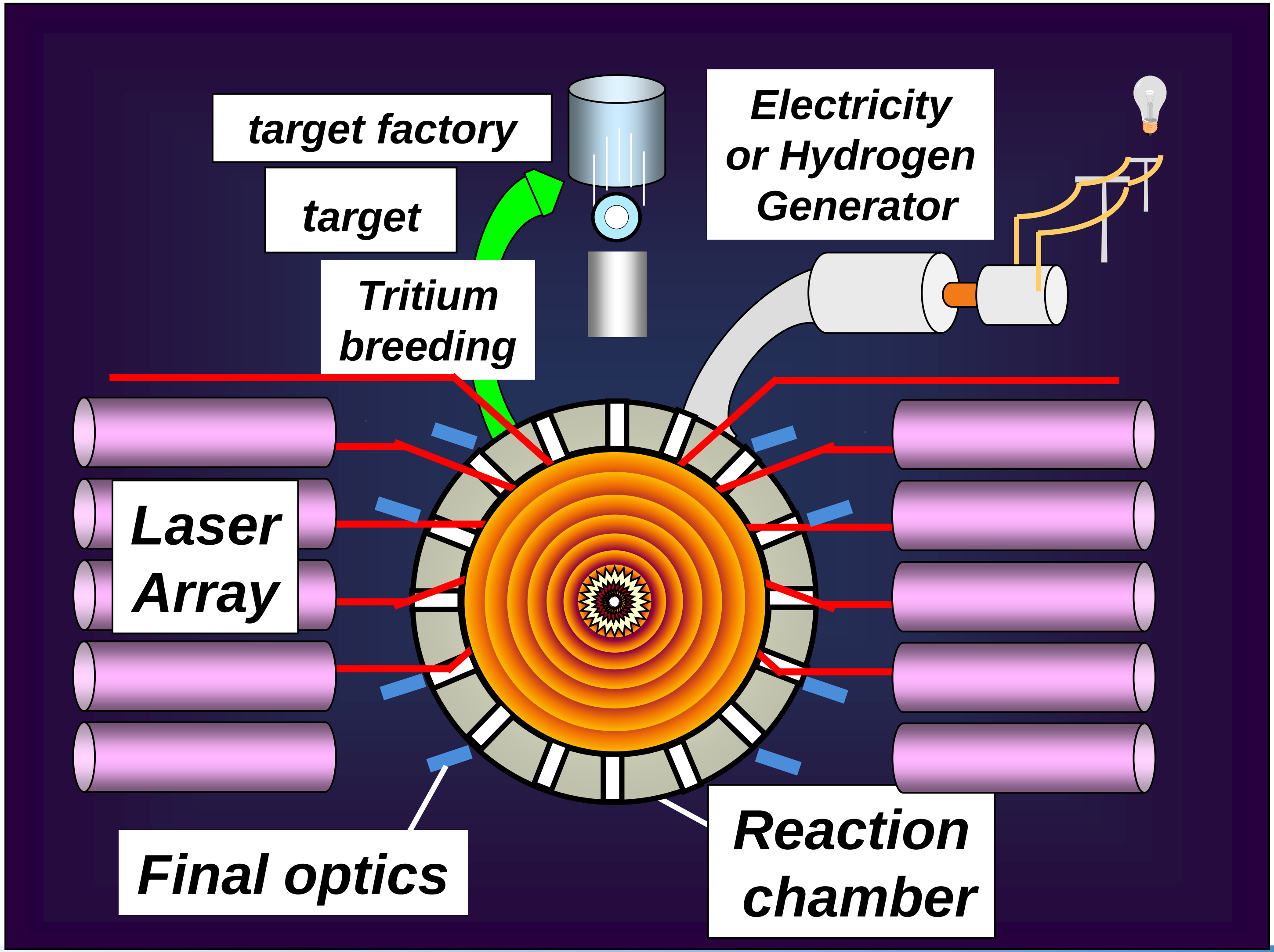
Fusion has the potential to meet all of these!



Advantages of the inertial fusion energy (IFE) concept:

- Significantly different technological risks than MFE
- Separable components
- Multiple target concepts with same driver
- Highly modular
- Technology and science spin-offs
- Multiple sponsors for key technologies (e.g., laser diodes, high neutron yield sources)

Inertial Fusion Power plant using laser drivers and DT fuel



For recirculating power <~25%, an important metric is ηG

- Driver efficiency, η
- Target gain, G

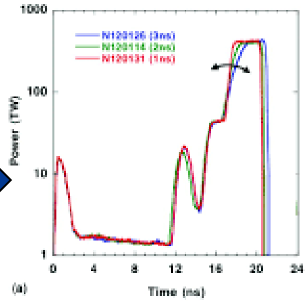
This is laser fusion now!

Capacitor banks (~400 MJ)

Flash lamps

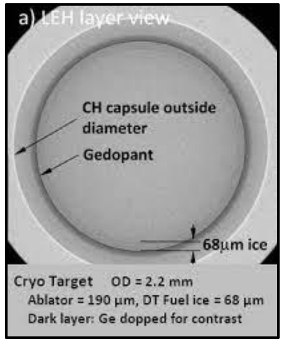
4 to 5 MJ at 1052-nm laser

Frequency conversion



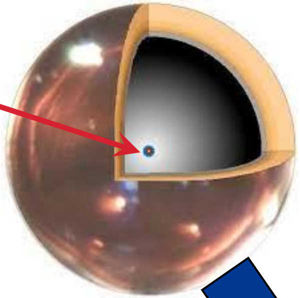
~2 MJ at 350 nm (~0.5% EO Efficiency)

~1.8 MJ at 300 eV blackbody Hohlraum



~0.2- to 0.3-MJ capsule

~0.03 MJ imploded target

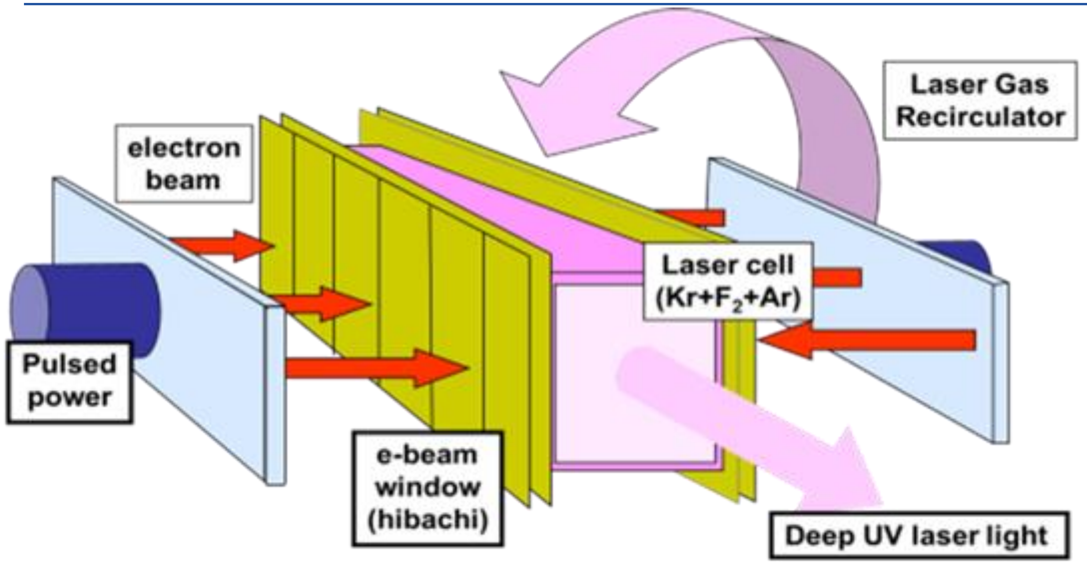


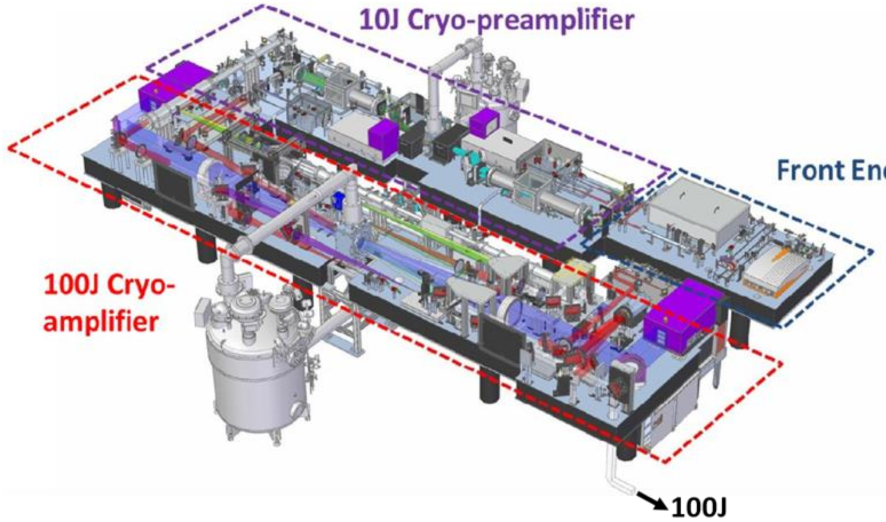
3.9 MJ of fusion energy (Gain ≈ 2)

Major research, engineering and technology development is required for the viability of laser-driven inertial fusion energy

- High Gains > 100 targets demonstration
- Rep-rated lasers at >10 Hz
- Clearing the target chamber at >10 Hz
- Mass production of targets at cost ~10-15 c/target
- Injection, survival and tracking of targets in the chamber
- First wall material development
- Tritium breeding and recovery
- Competitive cost of kWh and reasonable capital costs
- High availability
- Safety and public acceptance

High repetition rates and high efficiencies are required for IFE laser drivers





Pulsed Power-driven Excimer gas lasers

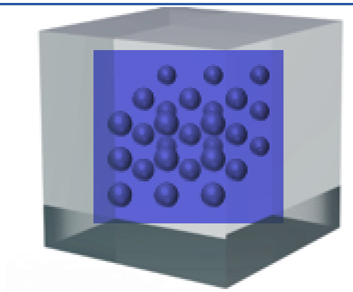
- Pulse Compression
    - Optical multiplexing (NRL: ArF (193 nm and 10 THz bandwidth)
    - Brillouin Pulse compression (Xcimer (KrF (ArF))

Diode pumped Solid State lasers

- Non-linear frequency conversion
- High Bandwidth

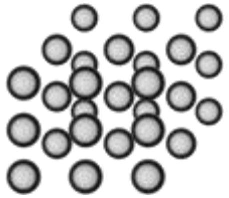
IFE targets must be mass produced

- **Holographic 3-D printing**



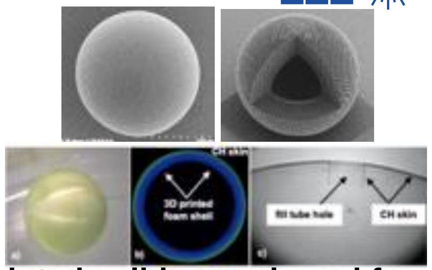
Holographic 3-D Exposure

Development in solvent



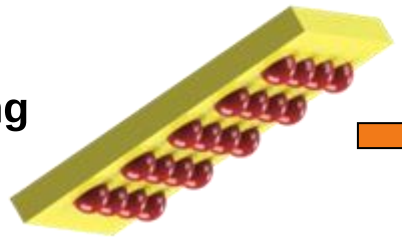
Batch targets produced in seconds to minutes

Targets for use



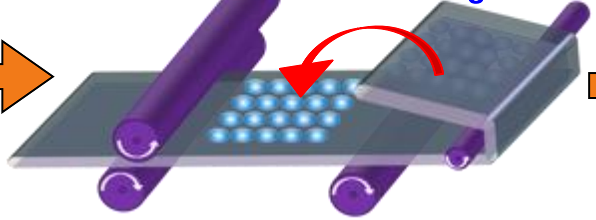
Printed solid capsule and foam targets (GA, UNL)

- **Nanoimprint and Origami Folding**

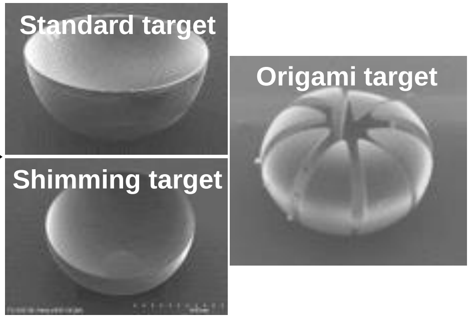


Laser manufactured mold

Origami folding to form entire targets

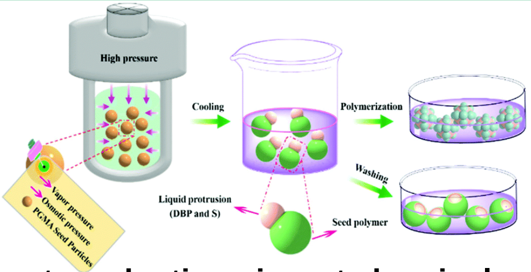


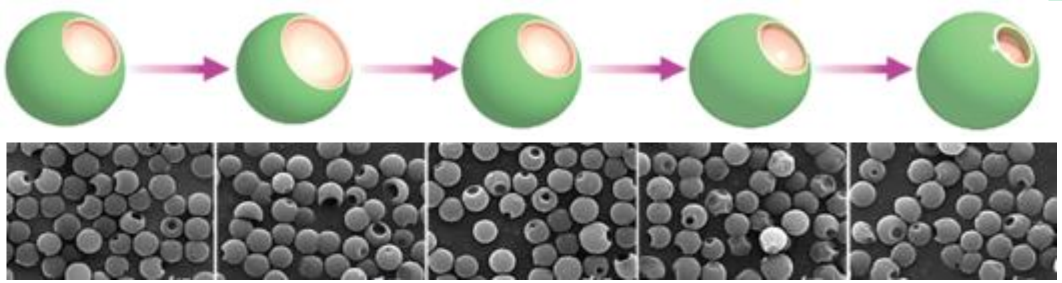
Roll-to-roll nanoimprinting of mass hemispherical targets



Standard, Shimming, Origami capsule targets (UNL)

- **Emulsion polymerization**





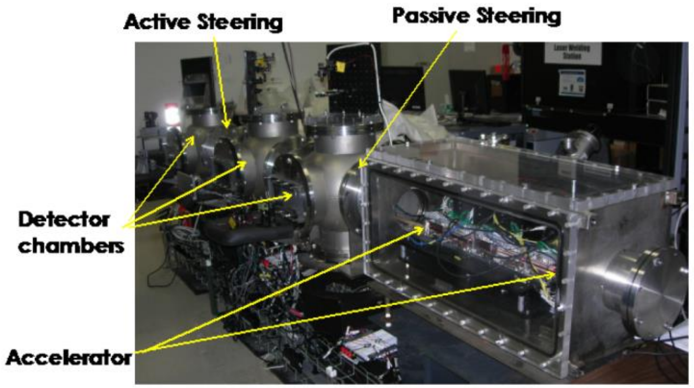
Mass target production via wet chemical processes

Polym. Chem., 2016, 7, 7078

Approaches to target injection, survival, and tracking must be developed

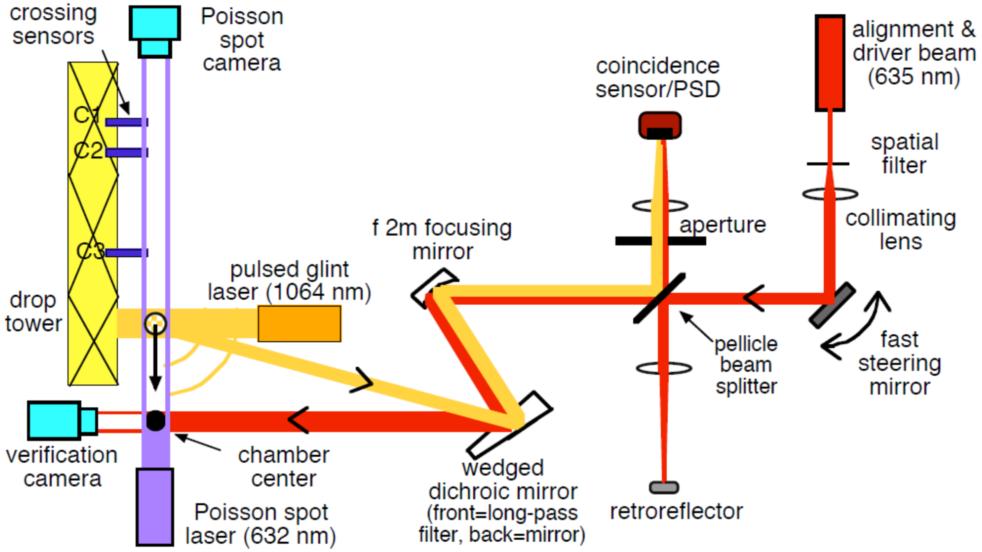
Injection

400 m/s gas gun



57 m/s Linear Induction Accelerator

Tracking



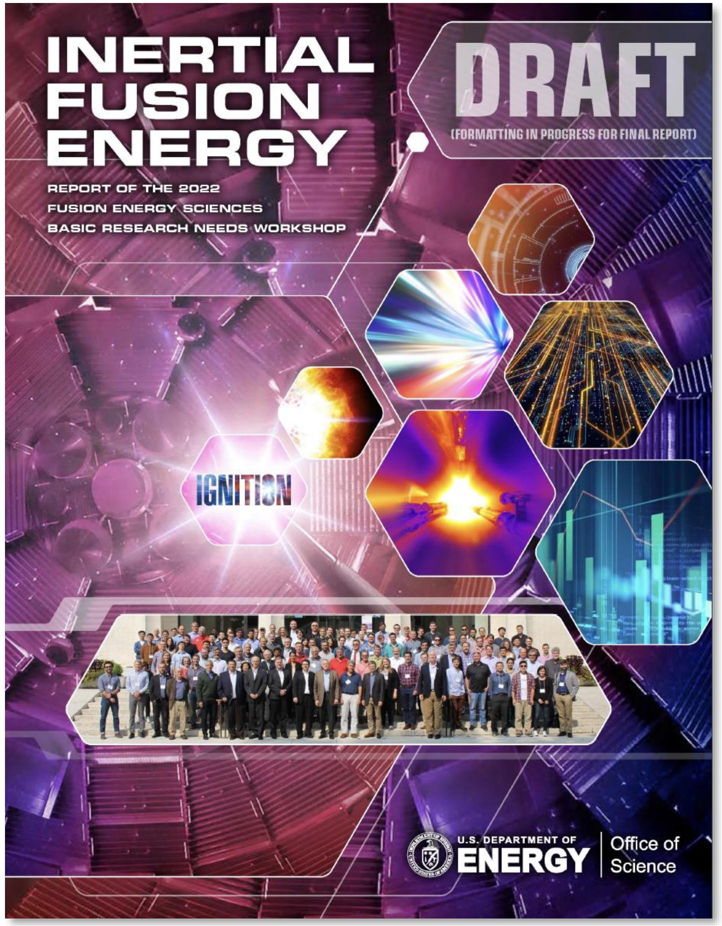
[1] *VG and material courtesy of Neil Alexander*

Magnetic and Inertial fusion energy plants based on DT fuel cycle share some common challenges

- Radiation flux and first wall survivability
  - Similar average neutron wall loads (~MW/m^2) but IFE is pulsed (~10 HZ) with higher peak power loading and x-rays and ions
    - Laser driven IFE has optics to be protected!
  - Several chamber concepts have been developed
    - Thick liquid wall
    - Dry walls with protective gas
- Tritium engineering/science
  - High-gain IFE targets will burn up ~30% of the fuel (tokamaks ~1% of the fuel)
  - Tritium breeding and recovery
    - Tritium present cost is ~$30,000/gram
  - Economics (breeding, recovery (blanket and chamber)

In 2022, the US DOE held a Basic Research Needs workshop to develop a national strategy for an IFE program

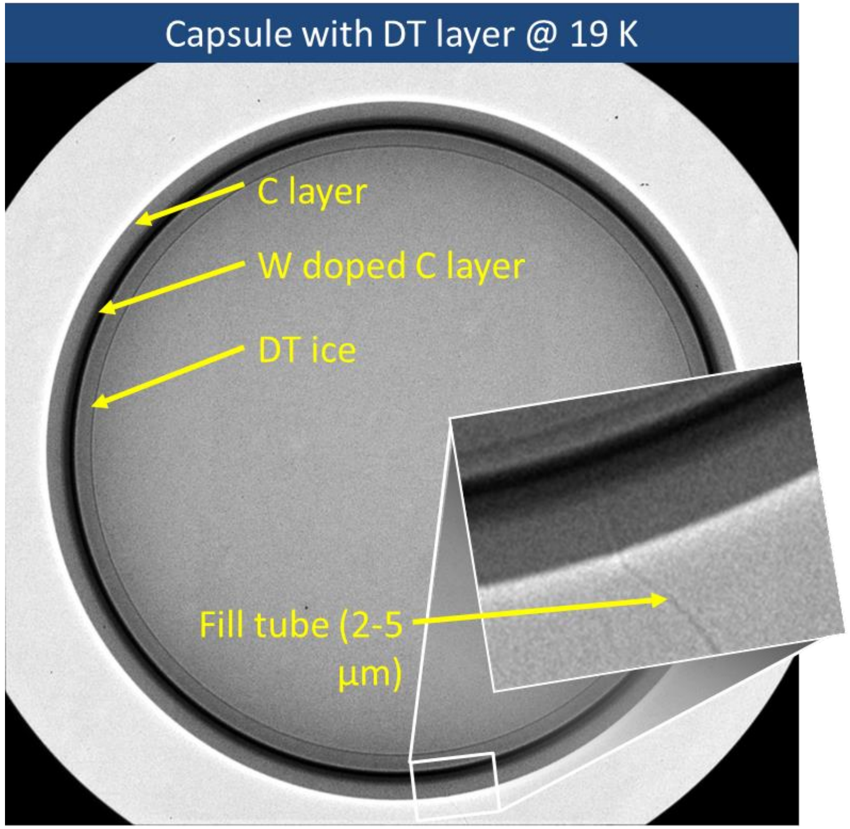
https://events.bizzabo.com/IFEBRN2022/home

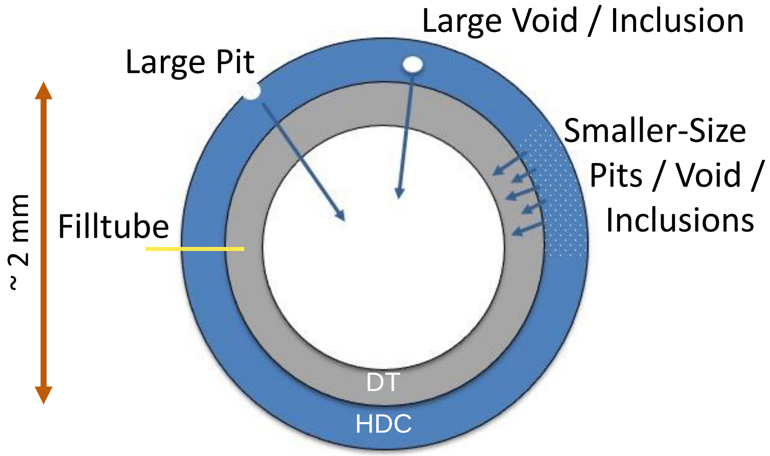


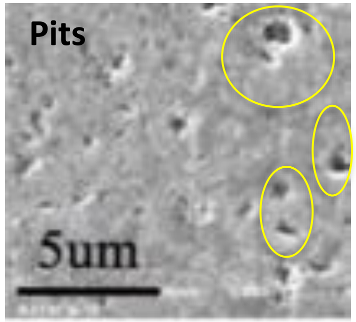
Report released Jan 2023

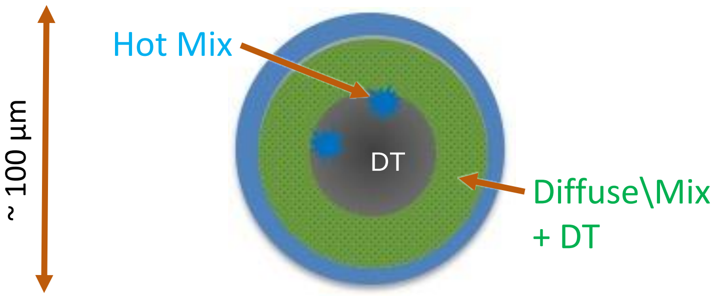
- **120 participants from US & international institutions**

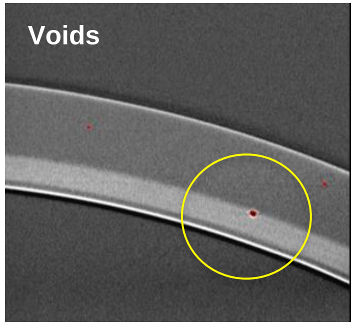
ICF capsules must be free of defects to prevent mixing of ablator material with the hot DT fusion fuel







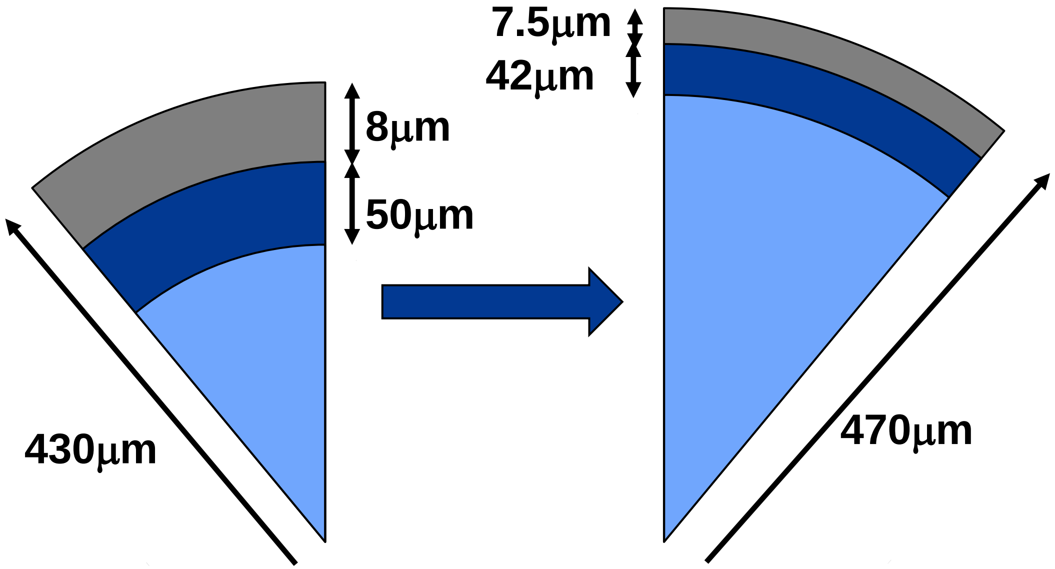




Courtesy of R. Town and B. Bechmann (LLNL)

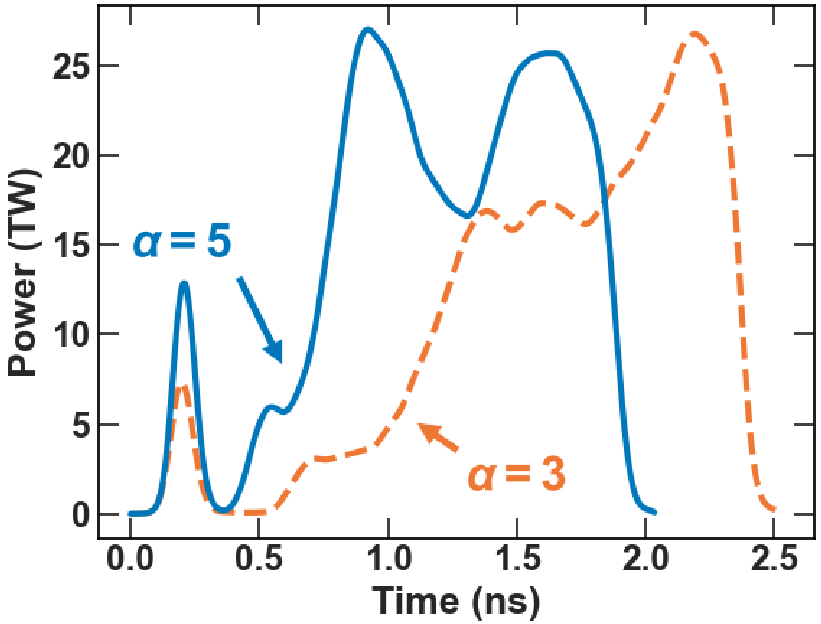
Laser pulse shape and target size were modified using statistical predictions. Age of the DT fill (fill-to-shot time) was reduced to three days

Targets have become
- larger (better energy coupling)
- thinner ice (faster)



This increases velocity, but also IFAR.
Higher adiabat required to maintain stability

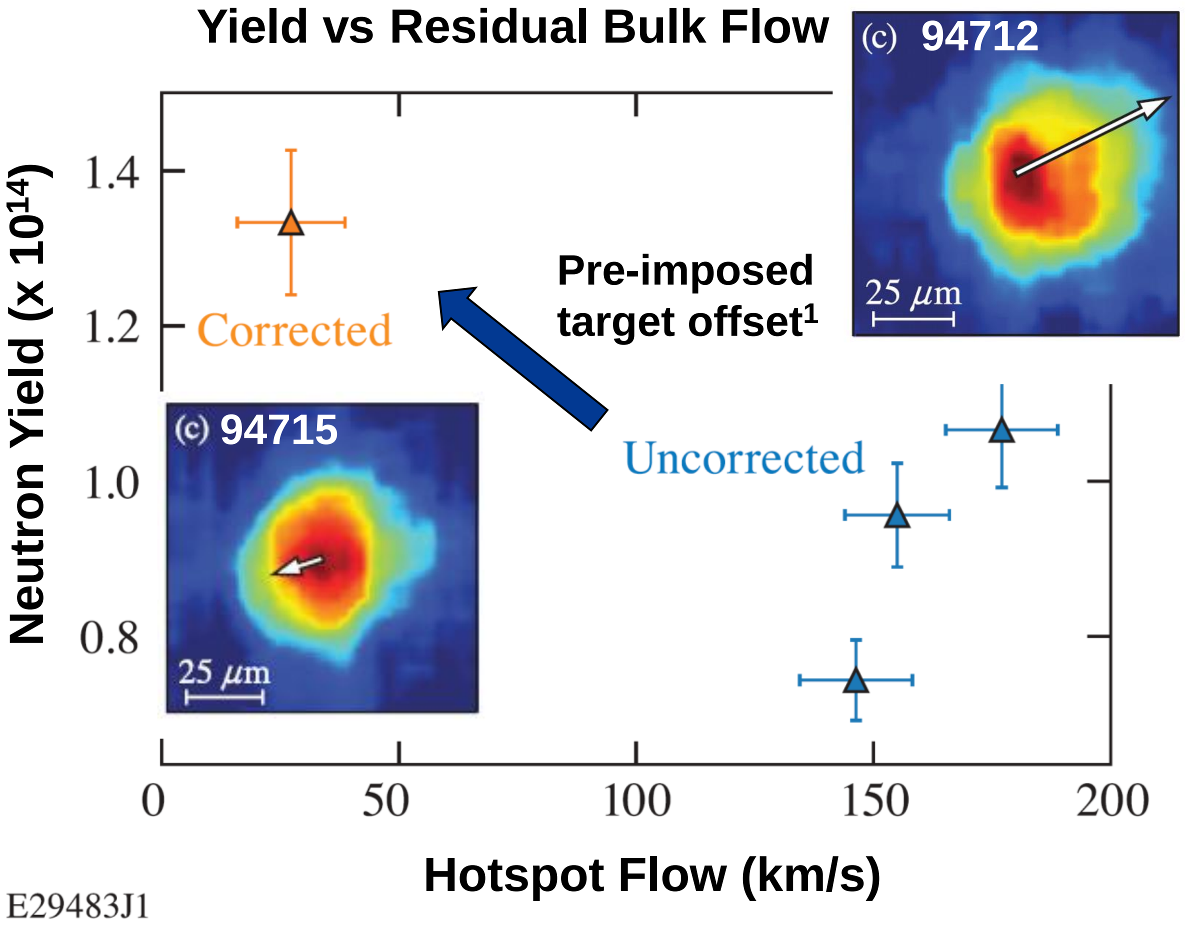
Pulse shape changes include:
- Higher picket (increases adiabat)
- Shorter pulse
- Increasing average peak power



Performance improved by increasing adiabat, IFAR and coupled energy, and by reducing degradation from He^3 with short 3-day DT fills.

IFAR: In-flight aspect ratio
CBET: Cross-beam energy transfer

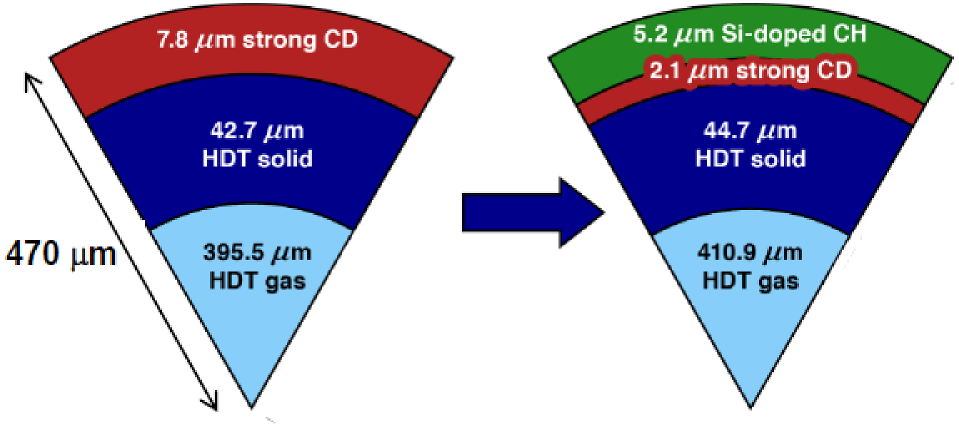
The degradation from mode 1 was mitigated through a pre-imposed offset obtained from nuclear measurement of the residual bulk flow[1,2]



[1] O Mannion et al, Phys. Plasmas 28, 042701 (2021)

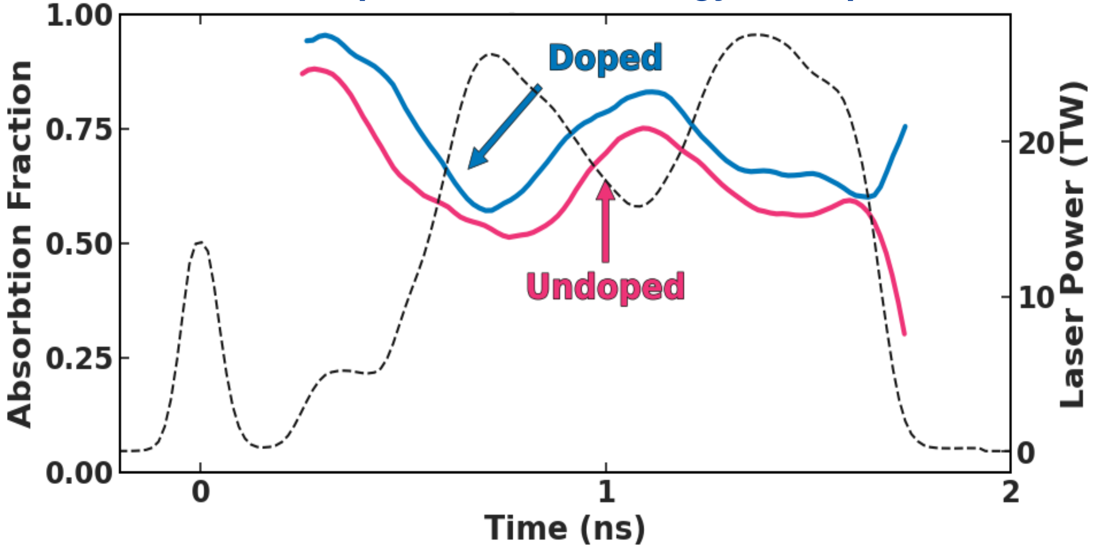
[2] A. Lees et al, IFSA 2023

Implosion energetics was improved by using 6% Si-doping in outer shell to increase laser absorption and suppress LPI

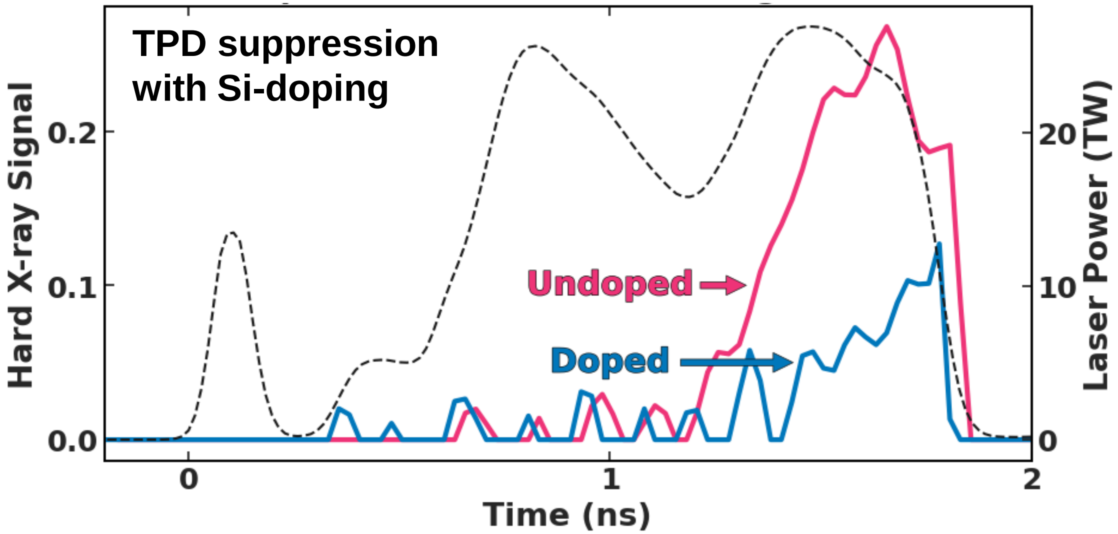


Shot 104949 (best performer, α=5)
Laser energy = 28.5 kJ
Yield = 2.1e14 (0.6 kJ)
ρR = 156 mg/cm^2
χ(2.1MJ)≈0.85

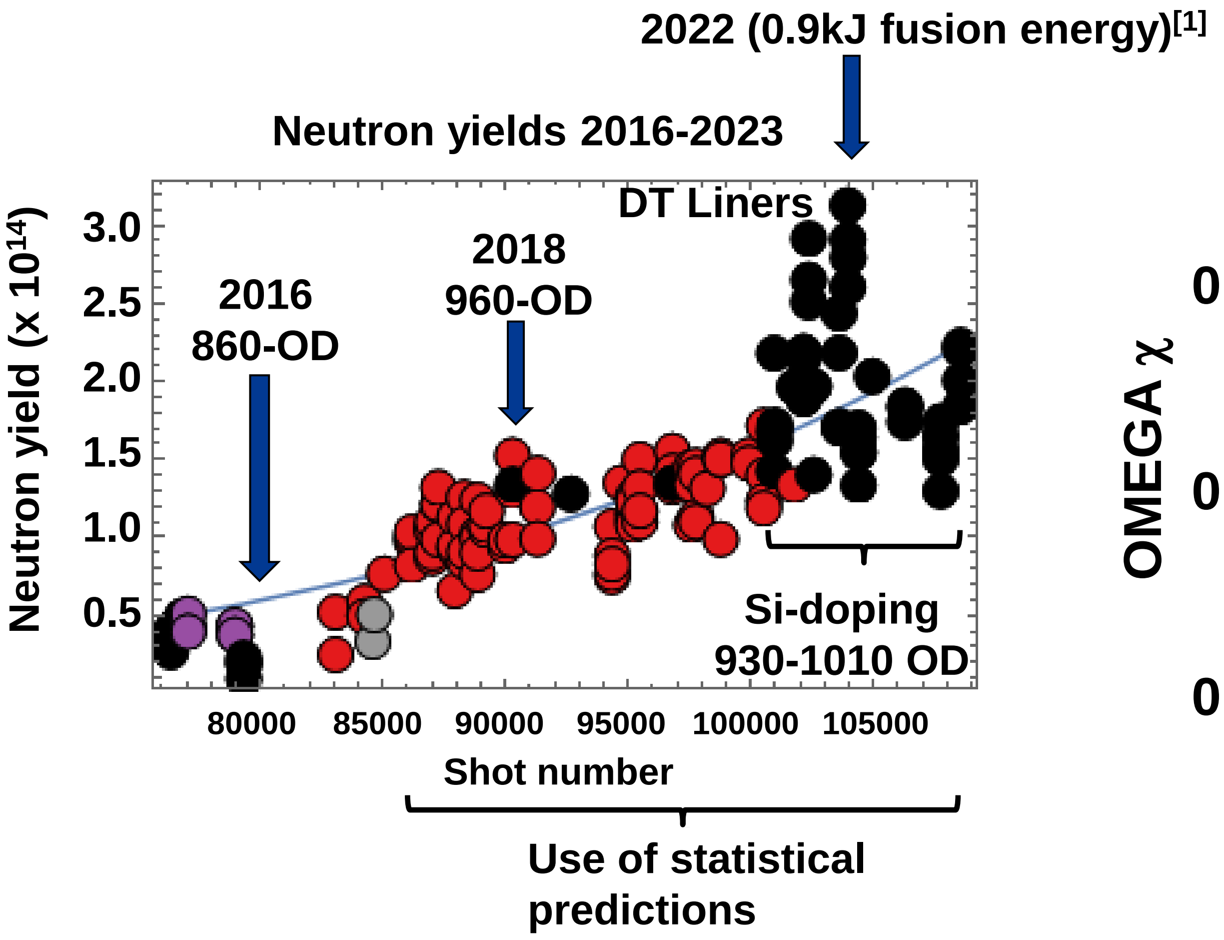
Time dependent laser-energy absorption

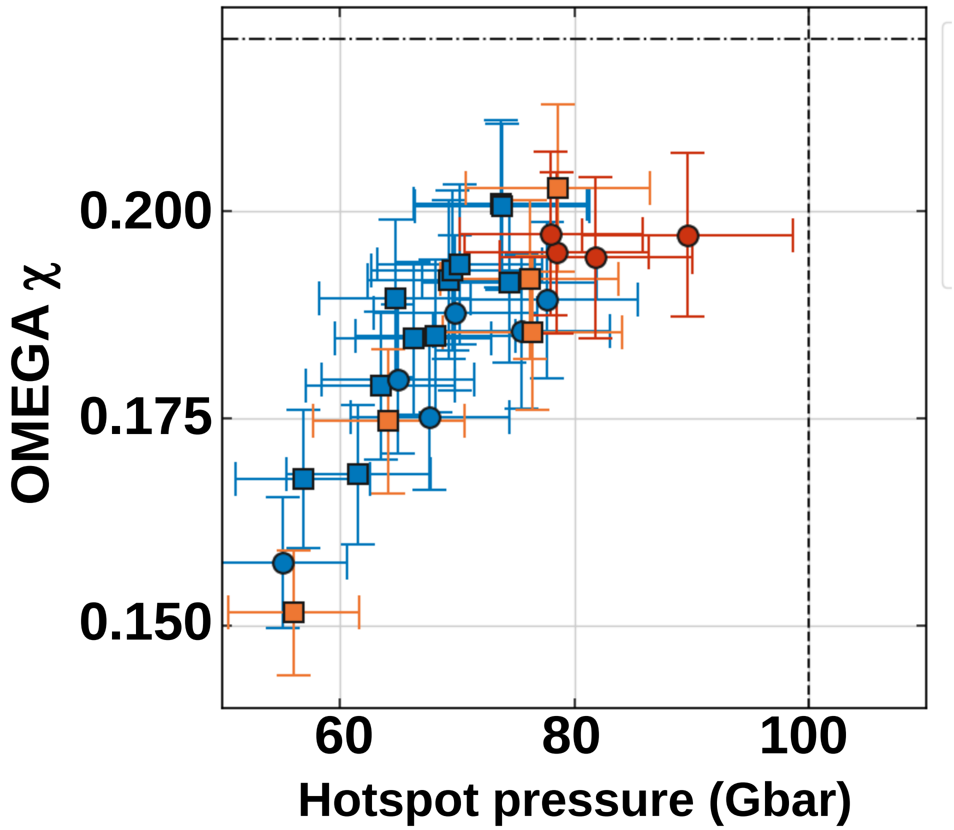


Hard X-ray signal from hot electrons (> 40keV)



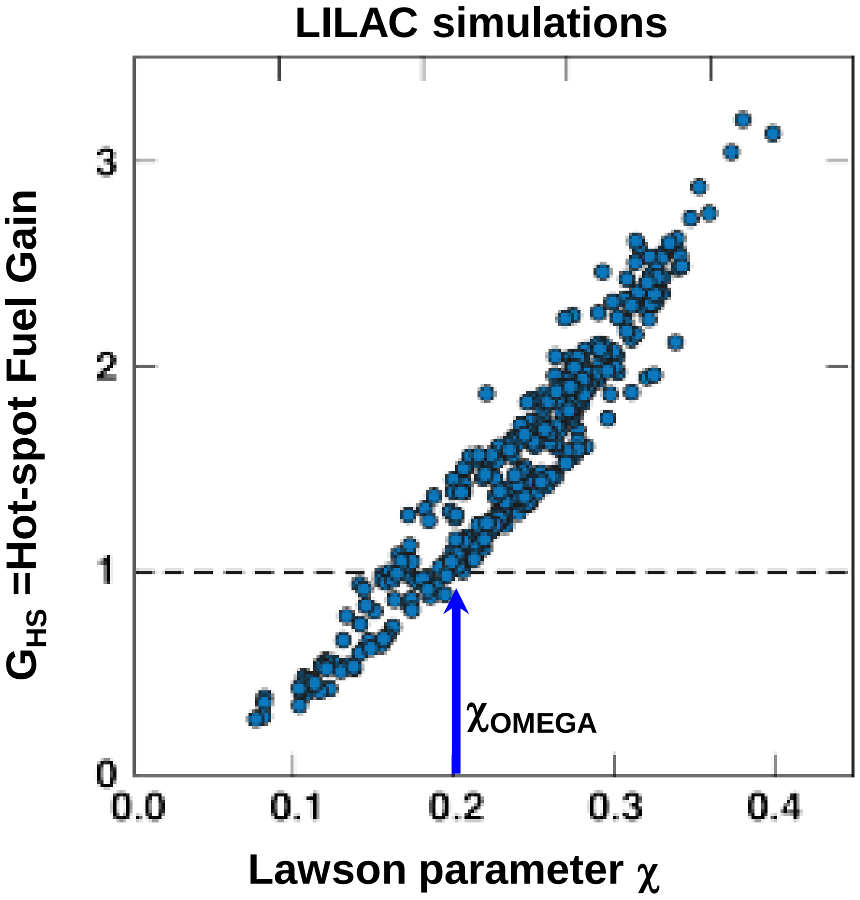
Fusion yield, Lawson parameter and hot spot pressure were improved through SM-guided designs and better energy coupling

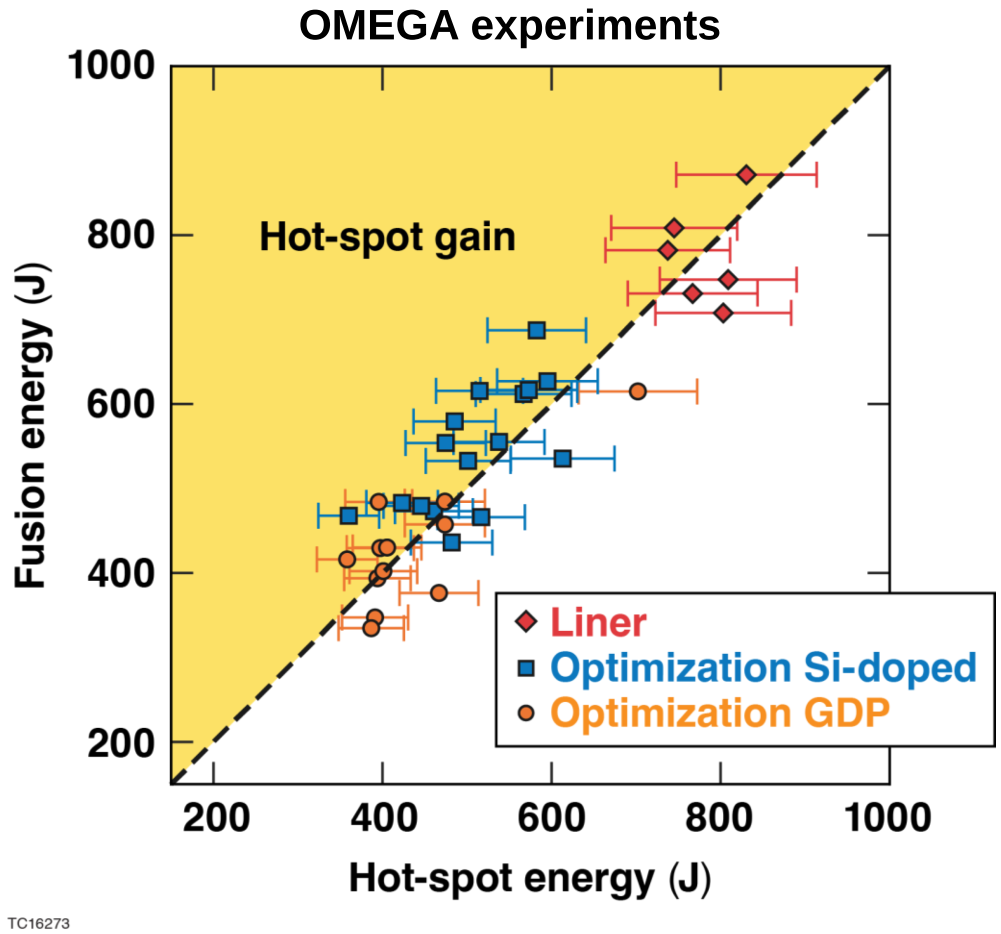




[1] Record yield achieved with high velocity DT liners
C. Williams et al, Phys. Plasmas 28, 122708 (2021)
[2] V. Gopalaswamy et al, accepted in Nature Physics

The current χ values corresponds to fusion energy outputs exceeding the internal energy of the fusing plasma[1]



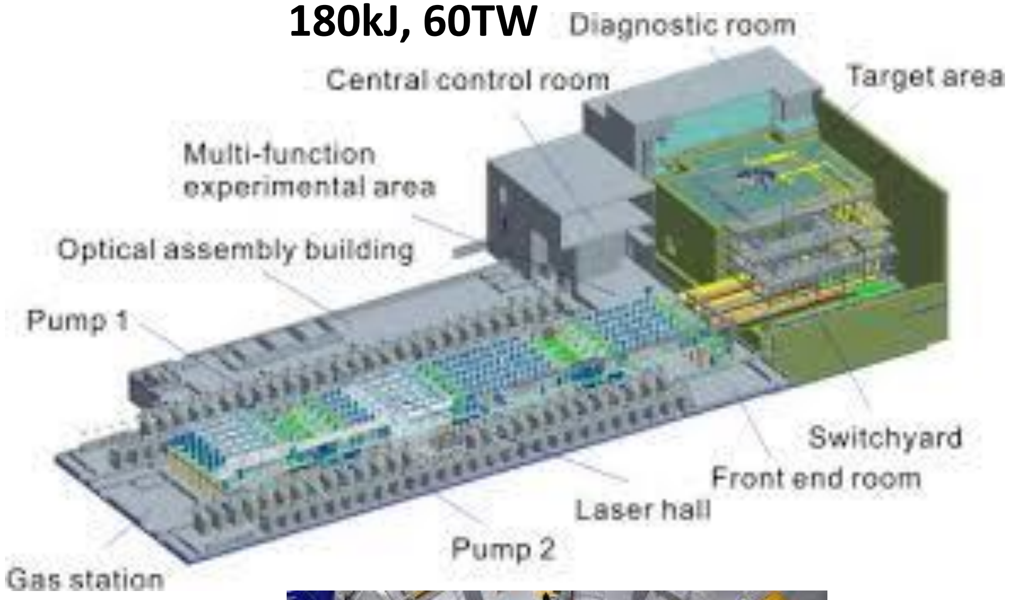


G_{HS} =Fusion Energy/Hot-spot Energy at $R_{17}^{18keV\text{-}xray}$

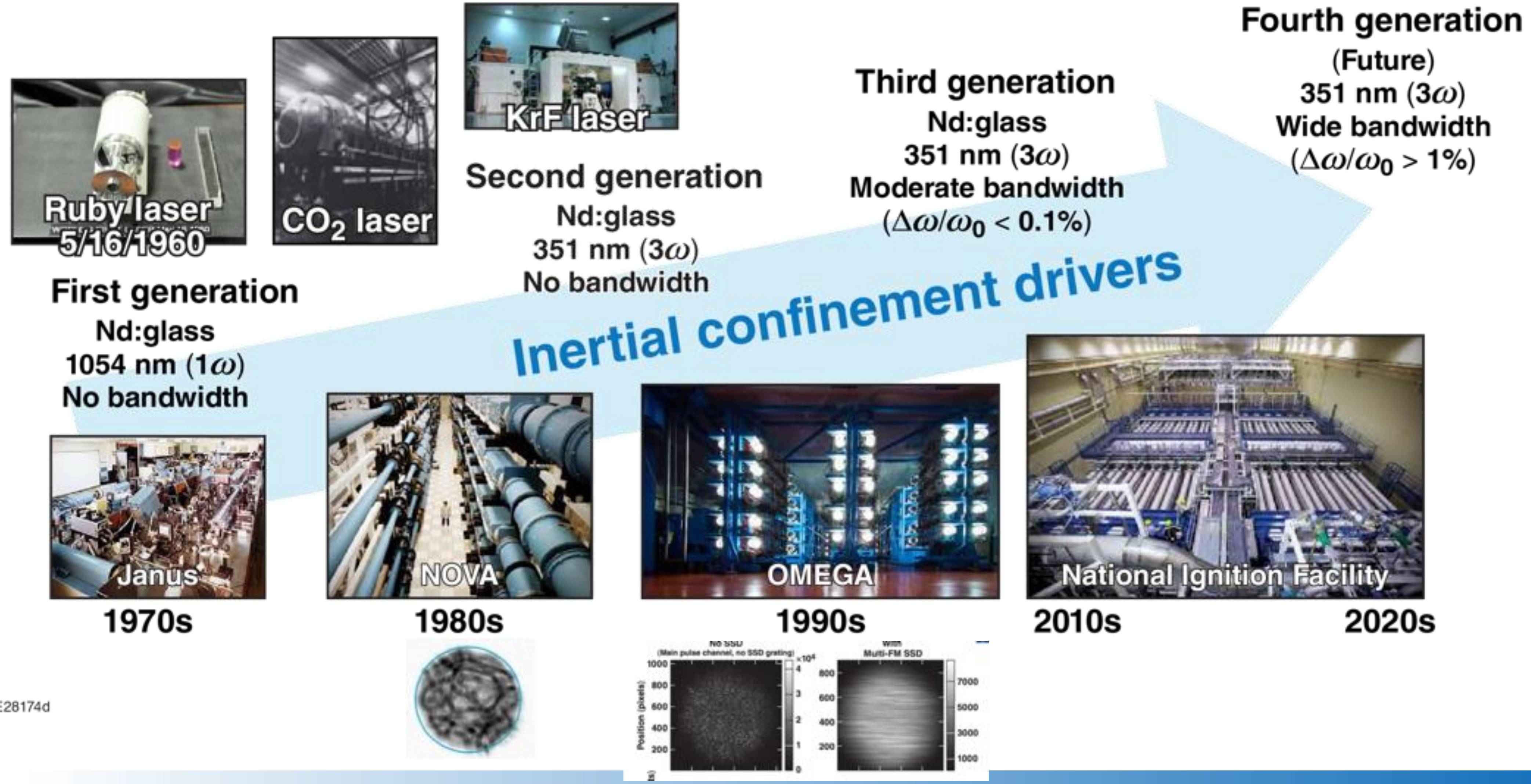
[1] C. Williams et al, accepted in Nature Physics

Other large laser-fusion implosion facilities operate outside the US. They can use both direct and indirect drive

SGIII (China)
180kJ, 60TW



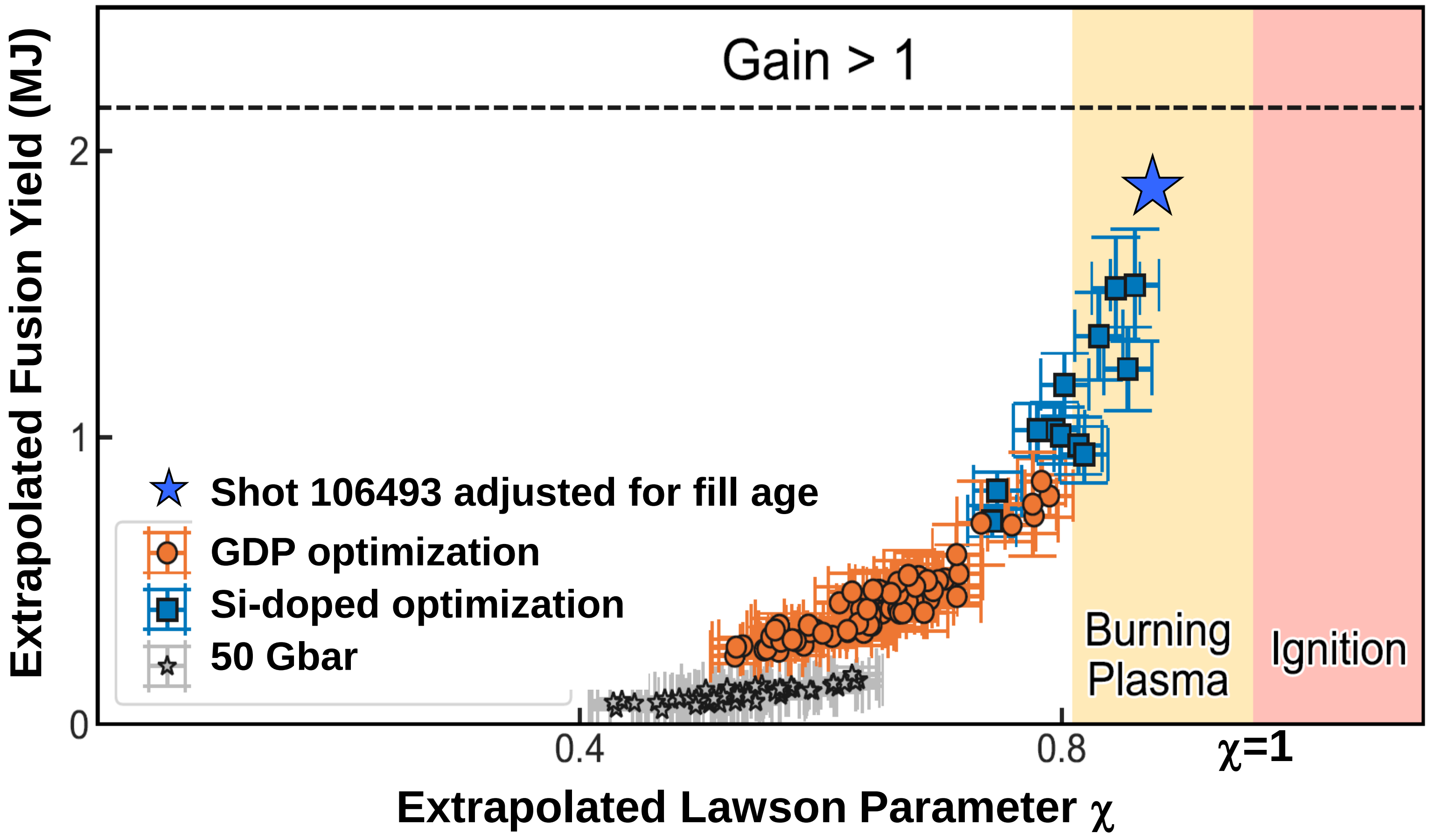
Present ICF/HEDP laser drivers are based on S&T developed in the 1980s and 1990s



E28174d

The extrapolated performance of OMEGA direct-drive implosions is close to the ignition threshold (90% of the Lawson parameter required for ignition)

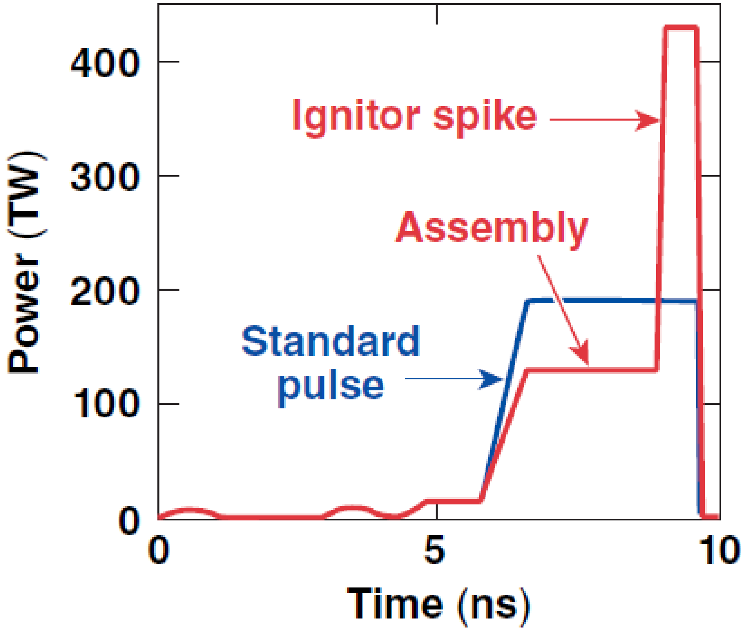
Fusion yield vs χ extrapolated to 2.1 MJ of laser energy*

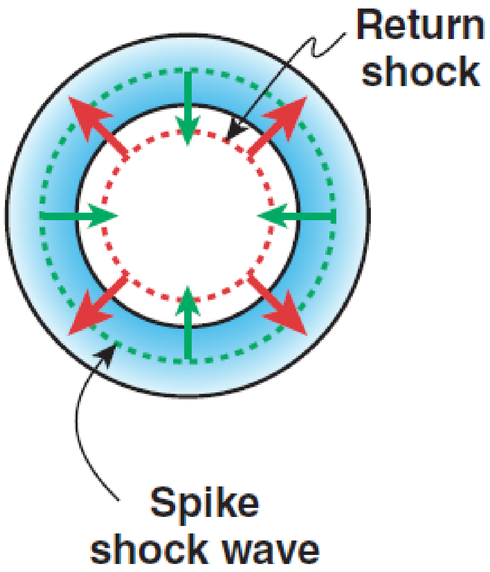


V. Gopalaswamy et al, accepted in Nature Physics

Other promising laser-fusion schemes are being studied in Europe, US, China and Japan in addition to conventional direct and indirect drive

Shock Ignition





Fast Ignition