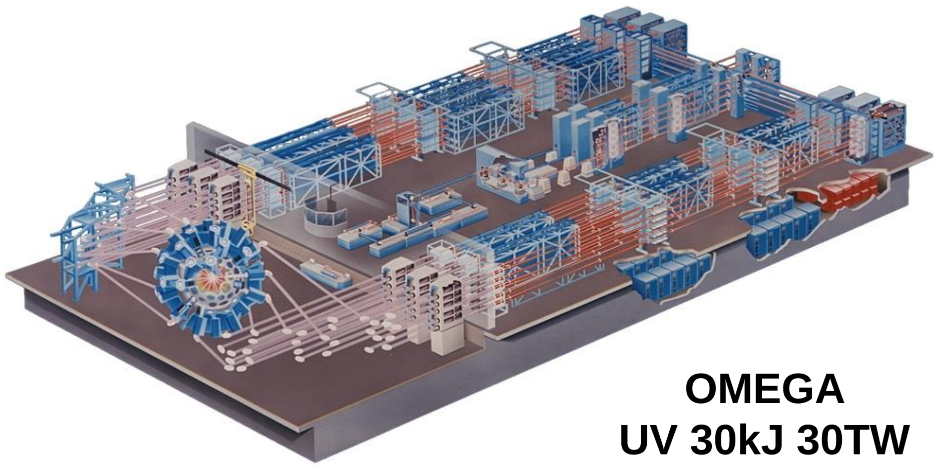
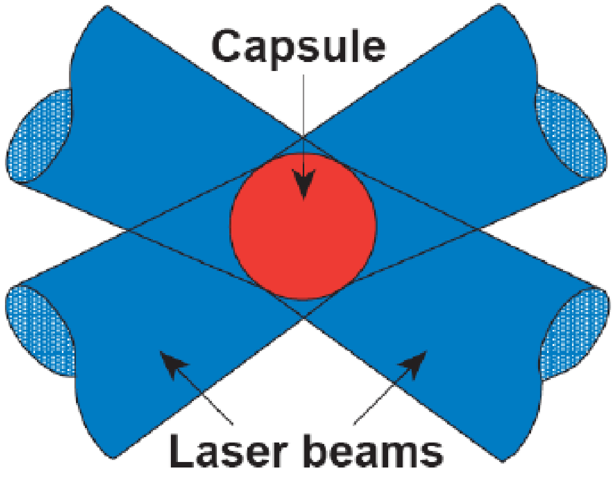
Progress in Laser Direct-Drive Inertial Confinement Fusion



OMEGA
UV 30kJ 30TW



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Nuclear Photonics Conference
Durham, NC
September 11-15, 2023

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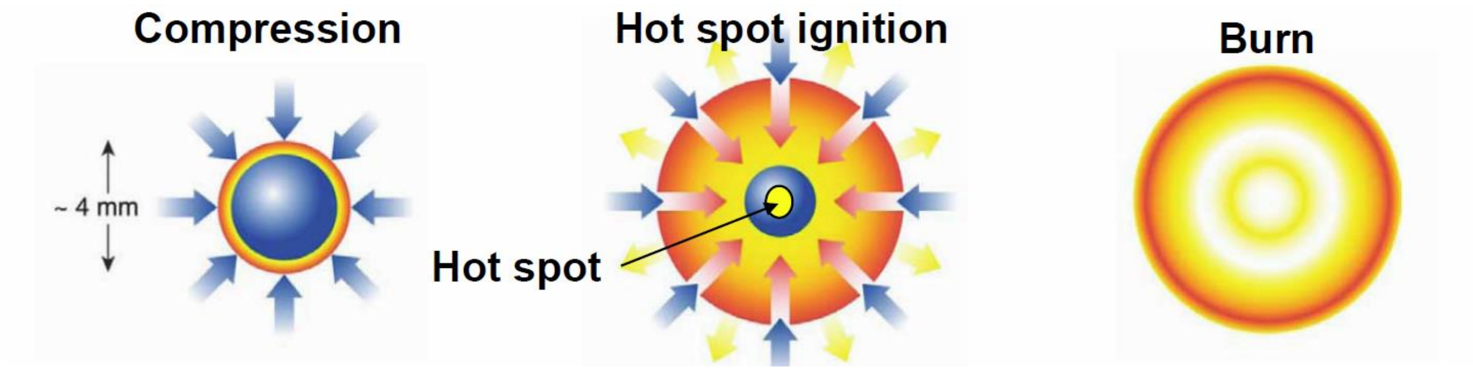
C. Shuldberg and M. Farrell

General Atomics

Introduction and implosion designs

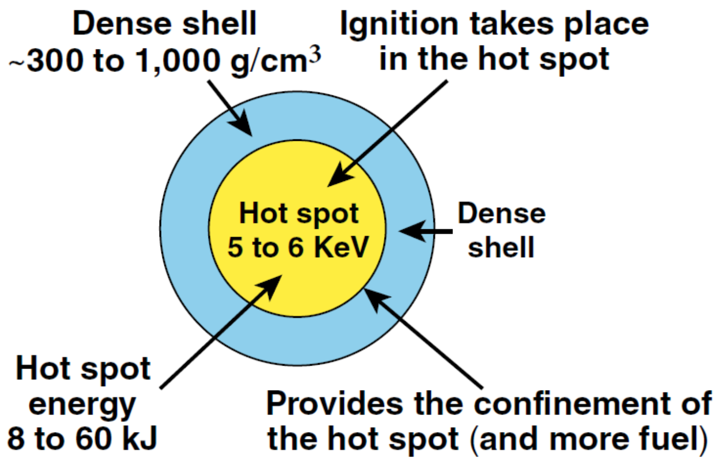
Both direct and indirect drive ICF aim to achieve the conditions for thermonuclear ignition and propagating burn

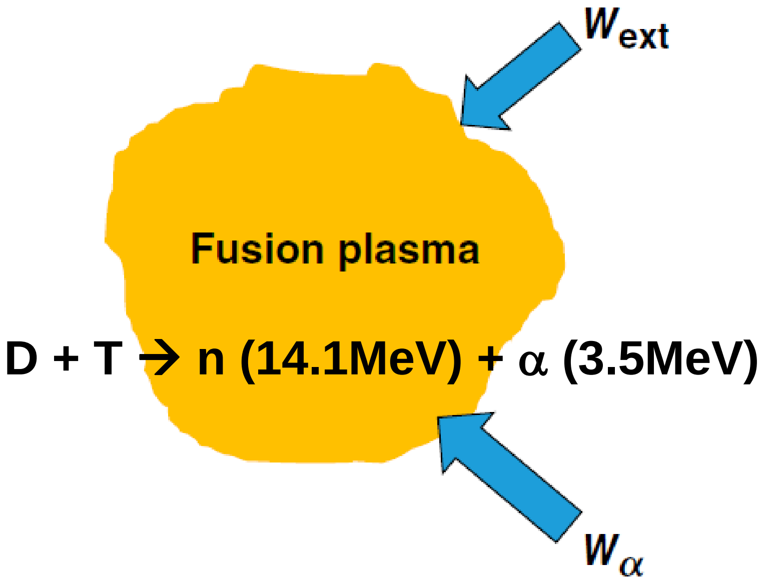


$$Q_\alpha \equiv \frac{W_\alpha}{W_{ext}}$$

In ICF $W_{ext} = W_{pdV}$

Compressed core at stagnation





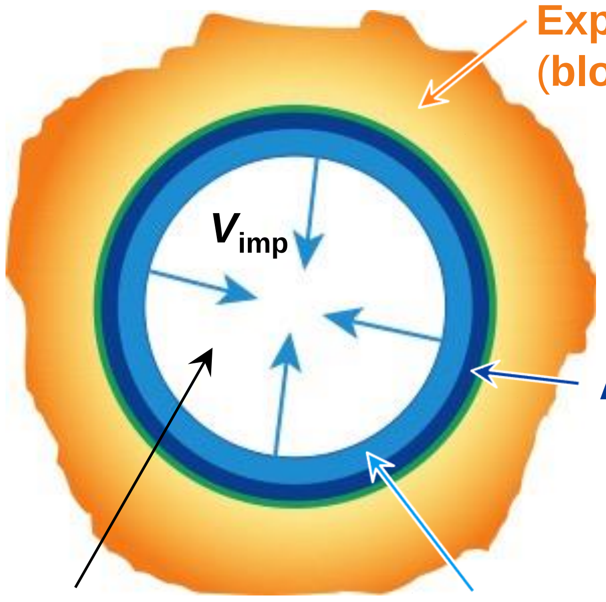
Burning plasmas

$Q_\alpha > 1$

Ignited plasmas

$Q_\alpha \gg 1$

Driving ICF targets with lasers is a very inefficient process. Direct drive couples more energy to the target than indirect drive



Examples:

Indirect Drive
Laser energy = 2 MJ
Shell final kinetic energy = 20-30 kJ
Total efficiency = 1-1.5%

Direct Drive
Laser energy = 2 MJ
Shell final kinetic energy = 80-100 kJ
Total efficiency = 4-5%

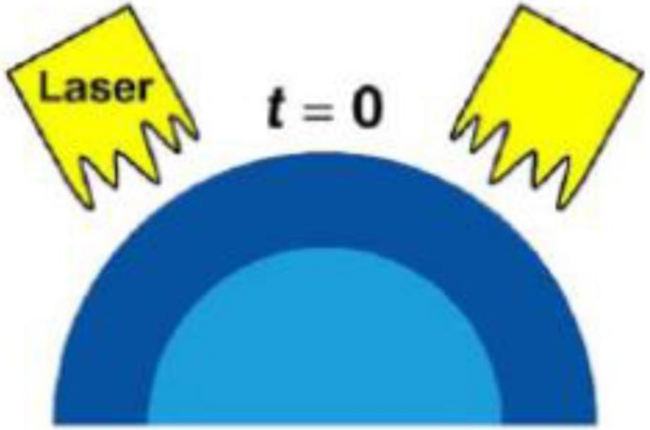
$$\text{Useful kinetic energy} = \frac{1}{2} M_{\text{unablated}}^{\text{shell}} V_{\text{imp}}^{2}$$

The favorable energetics implies that direct drive can potentially implode larger capsules containing more fuel thus leading to higher fusion yields and higher energy gains than indirect drive

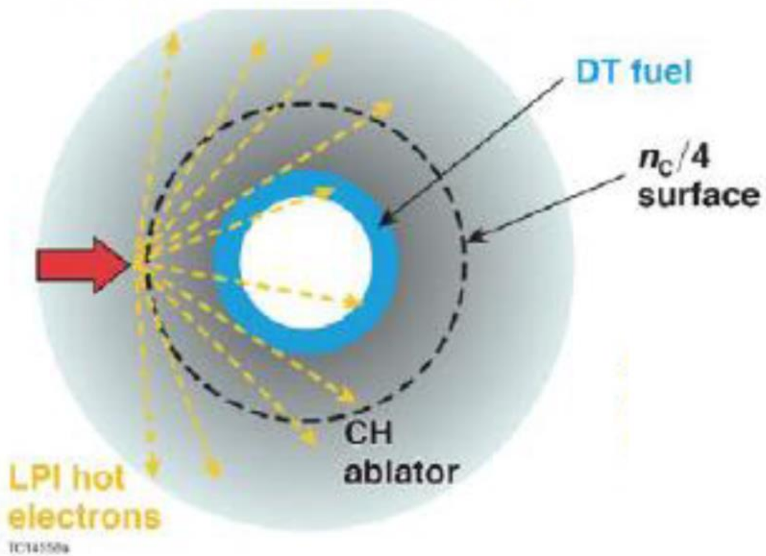
V_{imp} = implosion velocity

Depending on the design, direct-drive implosions are degraded by hydrodynamic and laser-plasma instabilities

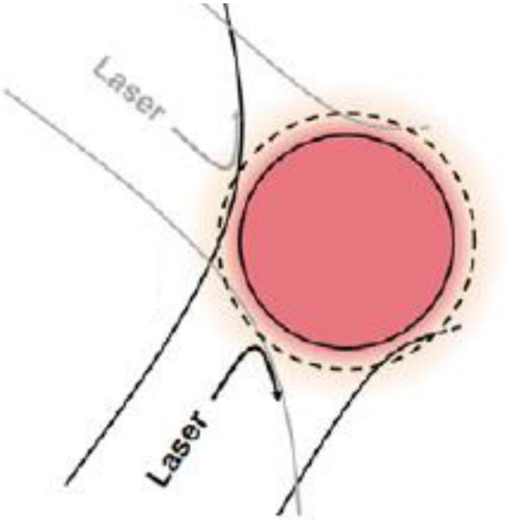
Laser imprinting seeds the Rayleigh-Taylor Instability



Hot electrons from Two-Plasmon Decay and Stimulated Raman Scattering preheat the target in-flight



Cross-Beam Energy Transfer reduces laser energy absorption



Hydro-stability metrics →

$$adiabat = \alpha_F \equiv \frac{P}{P_{Fermi}}$$

$$\text{IFAR} \equiv \frac{Radius}{Thickness}$$

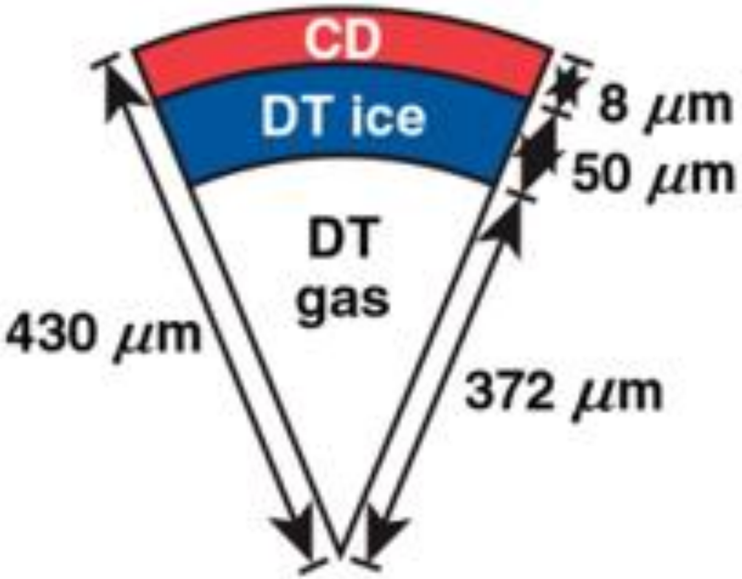
The adiabat is mostly set by the strength of the first shock

Higher α_F → more stable

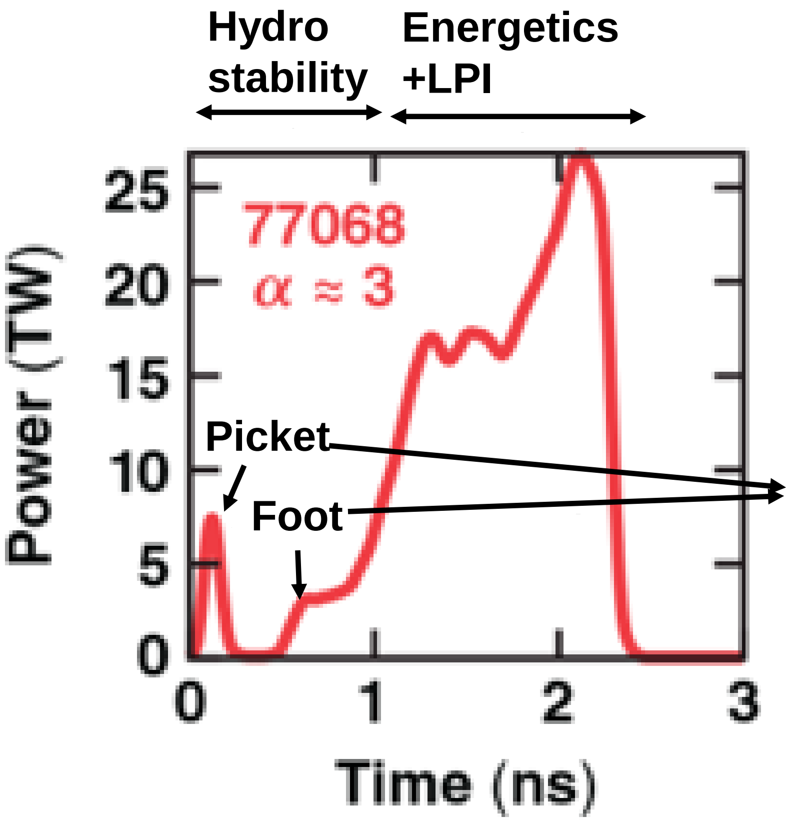
Higher IFAR → more unstable

Designing implosions requires achieving an optimal balance between 1D performance and 3D hydro-stability while controlling LPI

OMEGA target



Laser pulse shape



Shocks are launched.
Stronger shock → higher adiabat
Adiabat is set
Stability properties are set

Low adiabat is good for 1D convergence/compression while high adiabat is good for 3D stability. Target specs and laser pulse shapes are the knobs we can turn for optimizing implosions

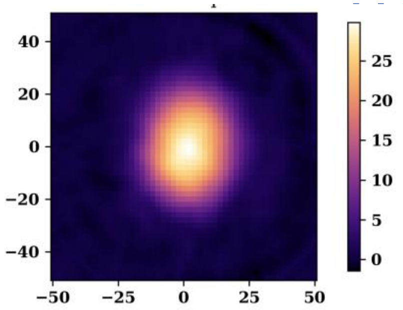
Fusion yield, burn duration, core size, pressure, density, temperature and areal density are the properties measured in implosion experiments

Inference of the core pressure and density

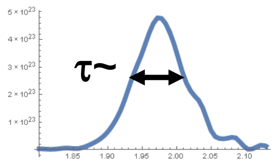
NTOF + Activation →

$$\text{Yield} \sim n_{HS}^2 \langle \sigma v \rangle V\tau \sim P_{HS}^2 \frac{\langle \sigma v \rangle}{T^2} V\tau$$

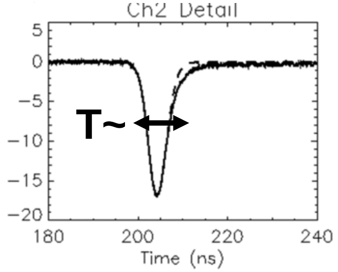
x ray

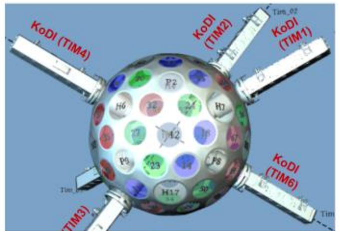


Neutron temporal diagnostic

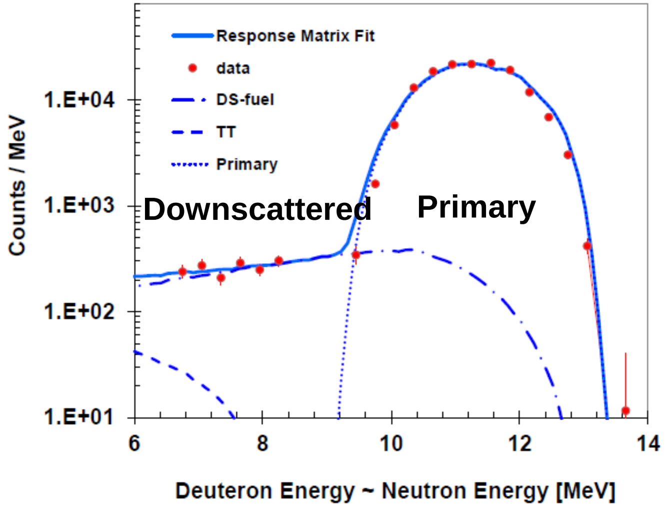


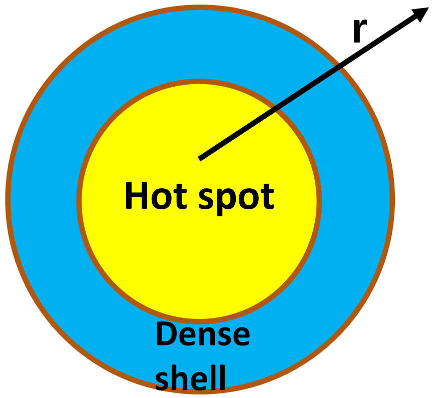
NTOF Brisk





Inference of the areal density





$$\rho R = \int_0^\infty \rho dr \sim \frac{\text{Downscattered}^{1}}{\text{Primary}} \sim \frac{\text{Backscattered}^{2}}{\text{Primary}}$$

[1] J. Frenje et al, Rev. Sci. Instrum. 72(1), 854–858 (2001)
[2] C. Forrest et al, *Rev. Sci. Instrum.* 83, 10D919 (2012)

A major goal of LLE is to produce scaled ignition conditions on OMEGA for direct drive

- **The measurable normalized ignition condition is determined by the Lawson parameter of the compressed core[1-4]**

Areal density (MRS, NTOF)

Neutron yield (NTOF+ Cu-activation)

$$\chi_{\exp} = \frac{nT\tau}{[nT\tau]_{ign}} \sim \left[(\rho R)^2 \left(\frac{Y_{DT}}{M_{DT}} \right) \right]^{1/3}$$

Stagnating DT mass (inferred)

- **When scaled hydrodynamically, the Lawson parameter increases linearly with size**

$$\chi \sim P\tau \sim \frac{P}{V_{imp}} R \sim R \qquad E_L \sim V \sim R^3 \Rightarrow R \sim E_L^{1/3}$$

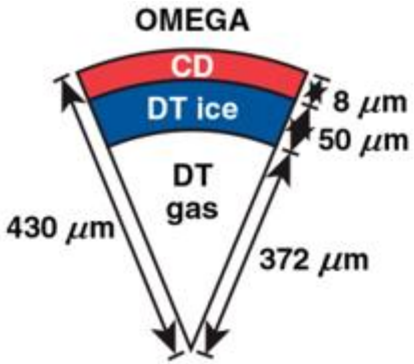
- **Hydro-equivalent Ignition condition →** $\chi_{MJ} \equiv \chi_{OMEGA} \left(\frac{E_L(MJ)}{E_{Laser}^{OMEGA}} \right)^{1/3} \geq 1$

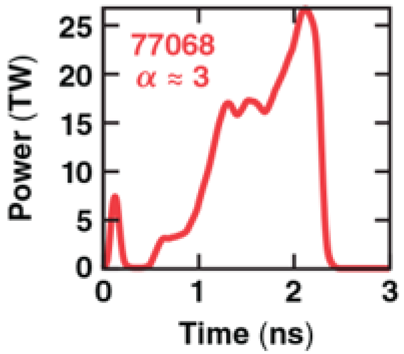
- **Hydro-equivalent Burning-Plasma condition[2] →** $\chi_{MJ} \geq 0.8$

[1] A. Christopherson et al, Phys. Plasmas 27, (2020)
[2] R. Betti et al, Phys. Rev. Lett. 114, 255003 (2015)
[3] J. D. Lindl et al. Phys. Plasmas 25, 122704 (2018)
[4] B.K. Spears et al, Phys. Plasmas 19, 056316 (2012)

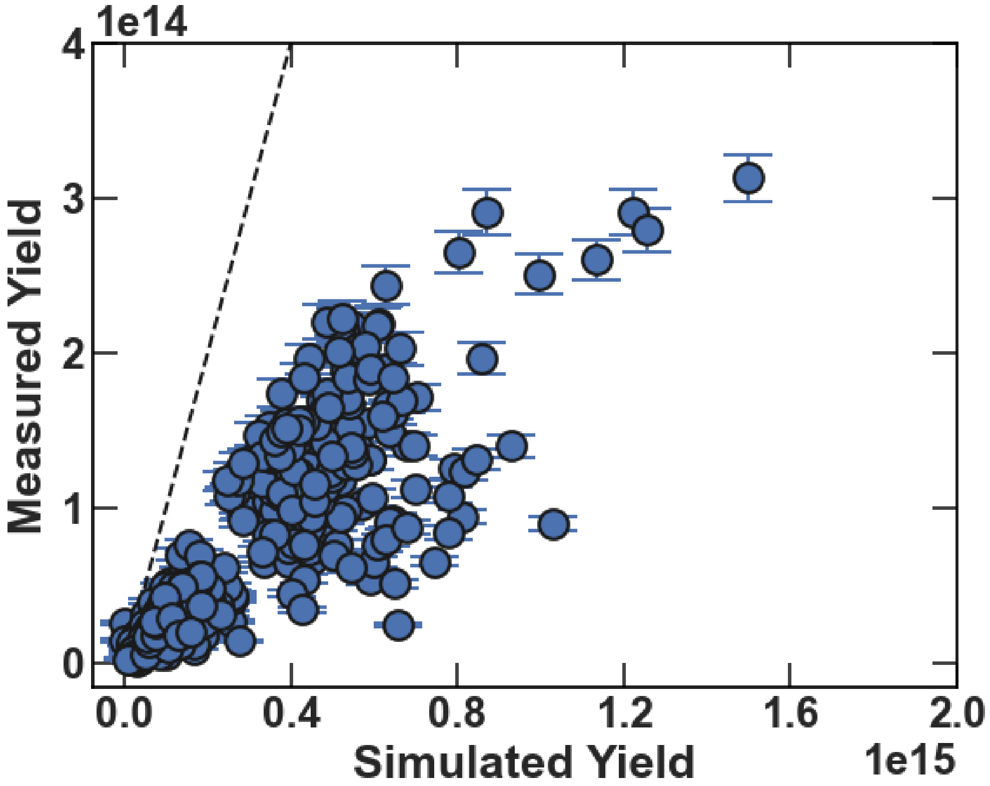
Conventional implosion designs use 1-D simulations, which are not accurate enough to guide designs towards optima

Initial Conditions



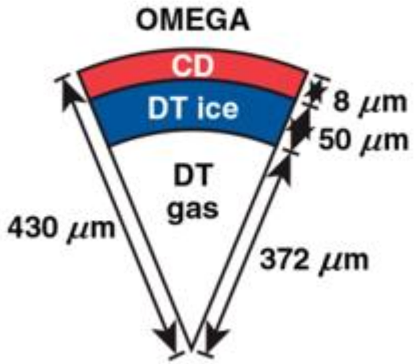


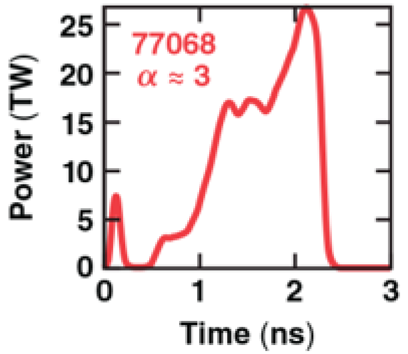
Simulations



LLE uses a data-driven statistical model (SM) to design high performance implosions

UR LLE

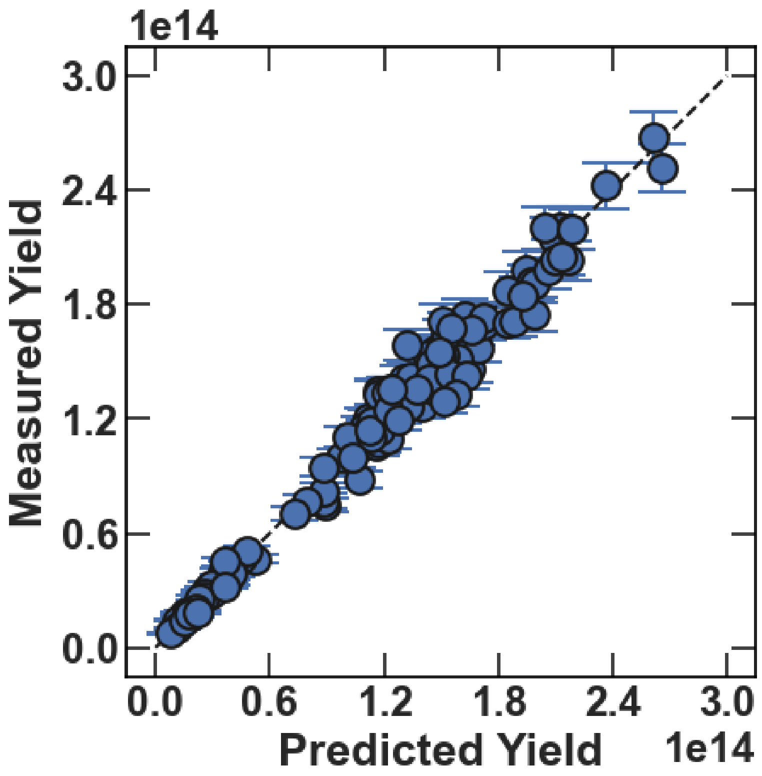




Simulation Predictions

Model trained on 300+ OMEGA experiments to find predictive transformations of simulations

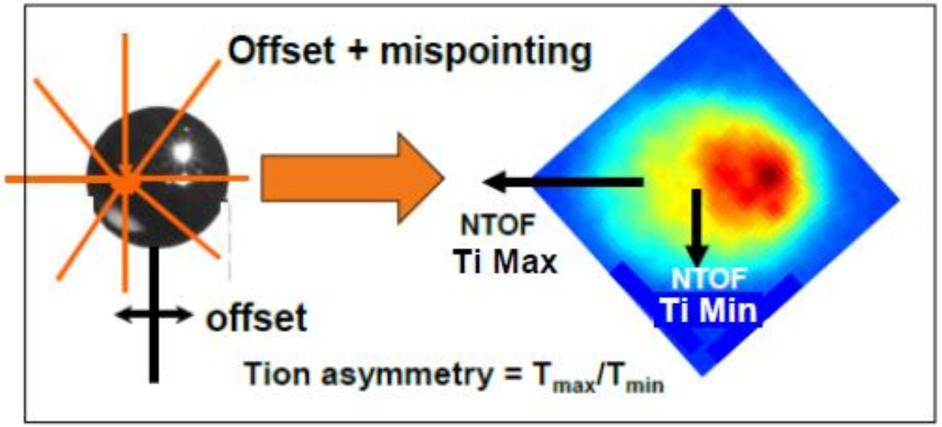
Measurements

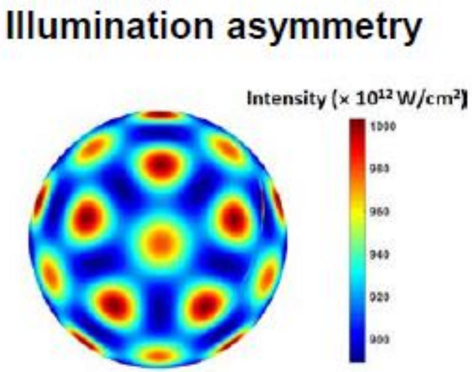


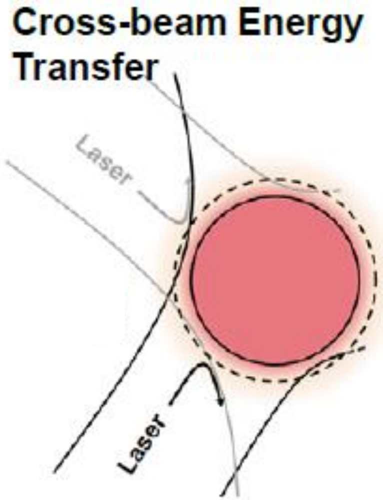
The model is accurate across a wide range of adiabats, convergence ratios, velocities and intensities

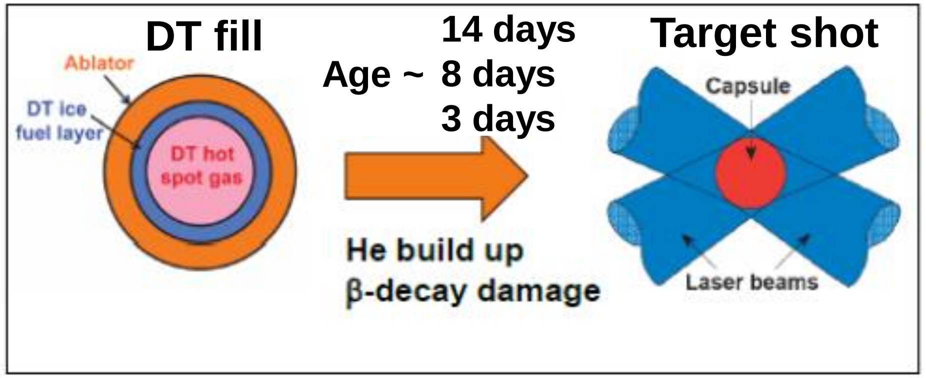
[1] V. Gopalaswamy et al, Nature 565, 581-586 (2019)
[2] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021)
[3] V. Gopalaswamy et al, PoP (2021)
[4] A. Lees et al, PoP (2023)

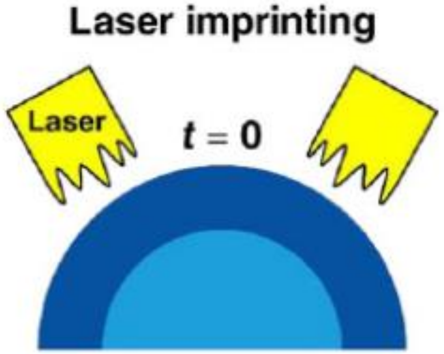
Many factors impact the performance of direct-drive implosions. The statistical predictions account for all these factors

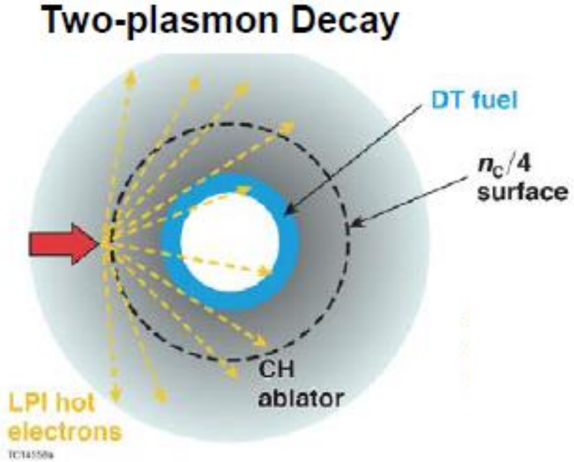












T_i = apparent ion temperature measured by NTOF detectors

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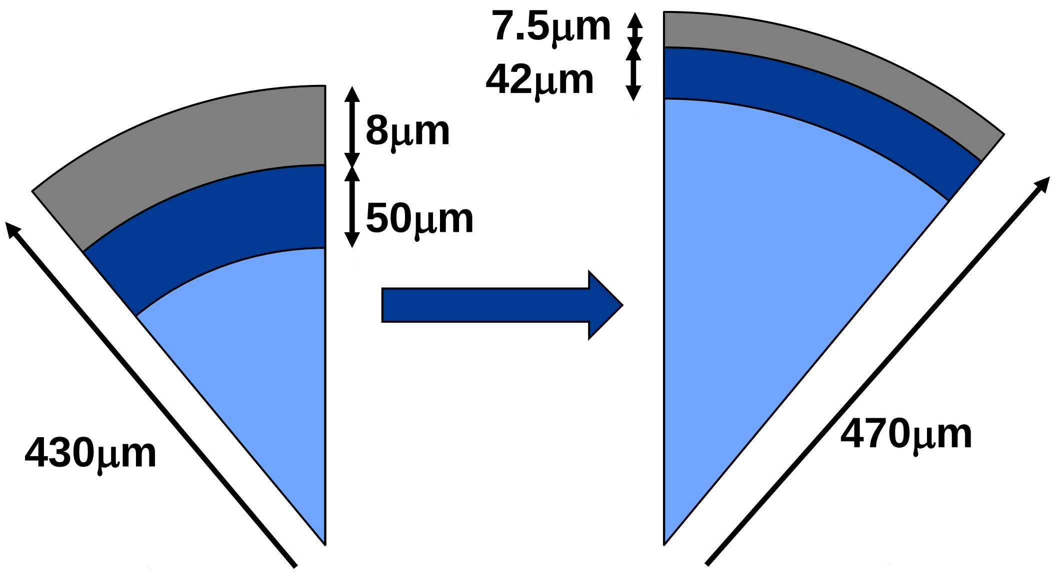
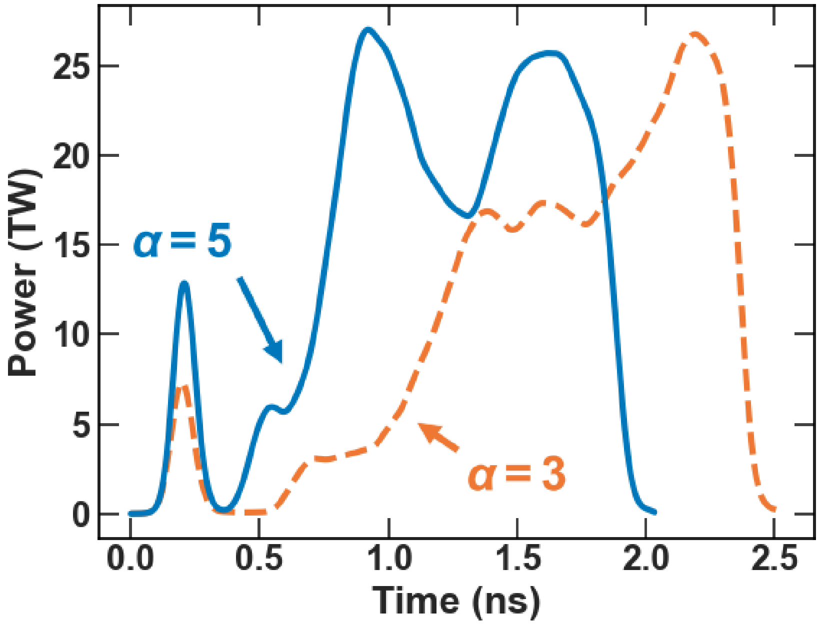
Laser pulse shape and target size were modified using statistical predictions. Age of the DT fill (fill-to-shot time) was reduced to three days

Targets have become
- larger (CBET mitigation)
- thinner ice (faster)



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

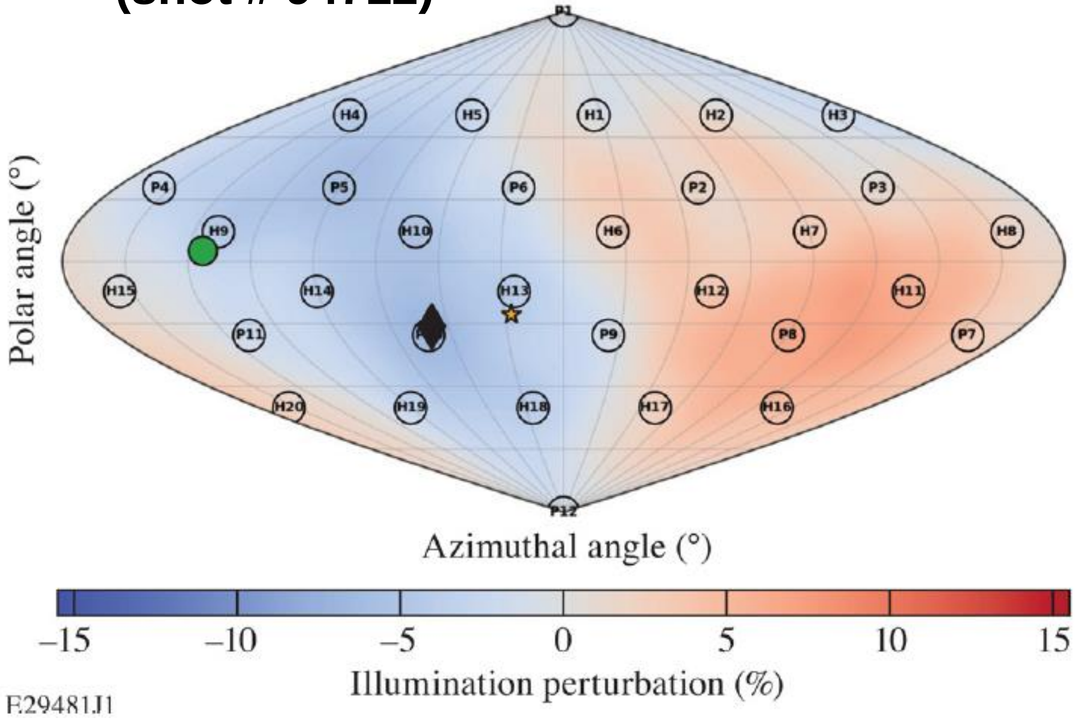


Performance improved by increasing adiabat, coupled energy and implosion velocity, and by reducing degradation from He^3 with short 3-day DT fills.

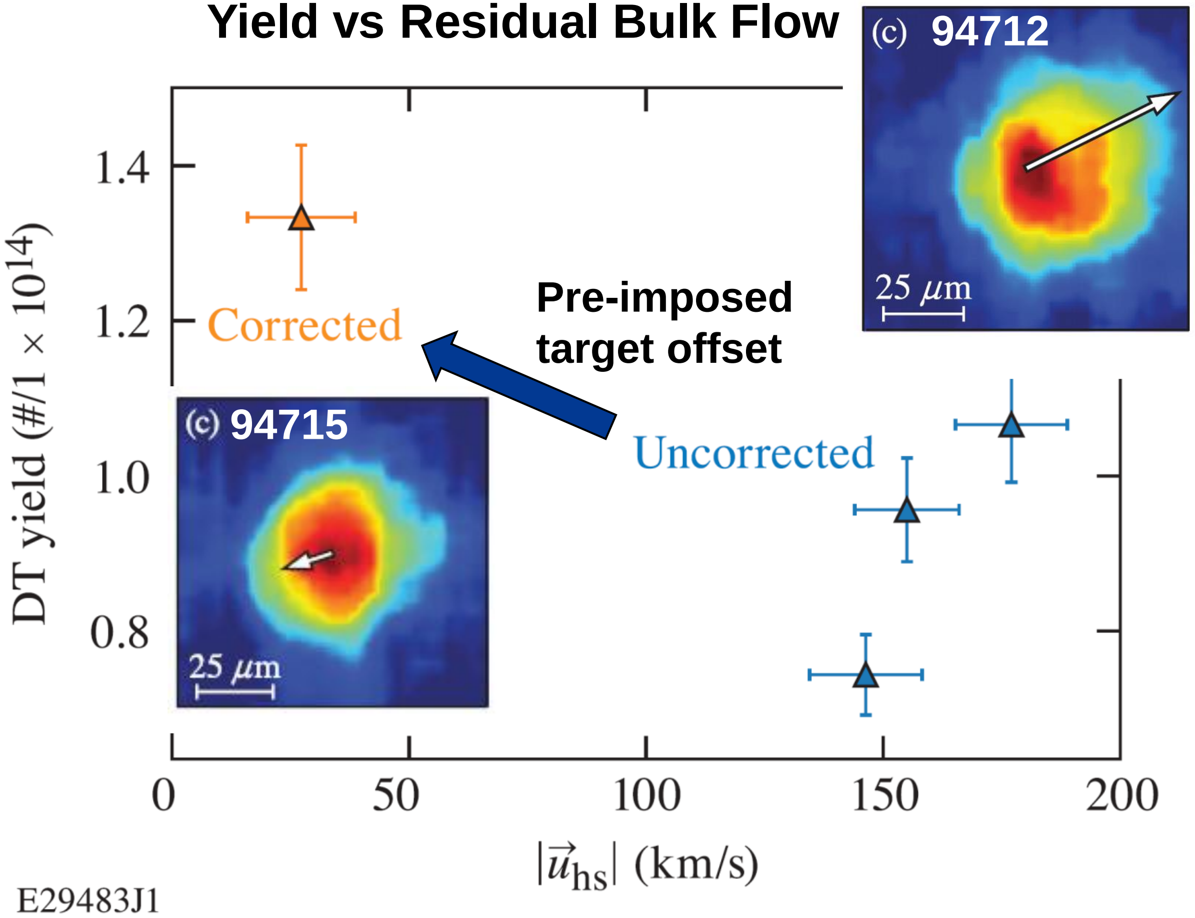
IFAR: In-flight aspect ratio
CBET: Cross-beam energy transfer

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

Hard-sphere projection of laser illumination (shot # 94712)

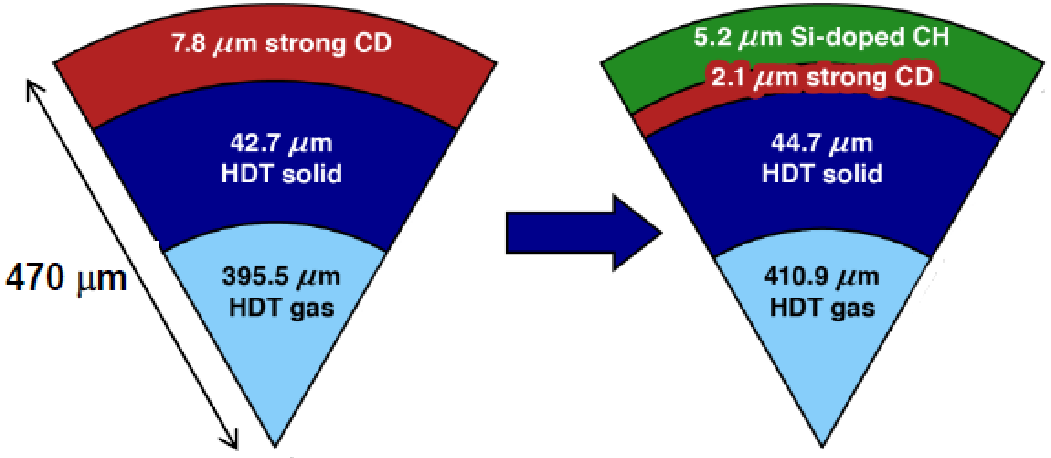


Yield vs Residual Bulk Flow



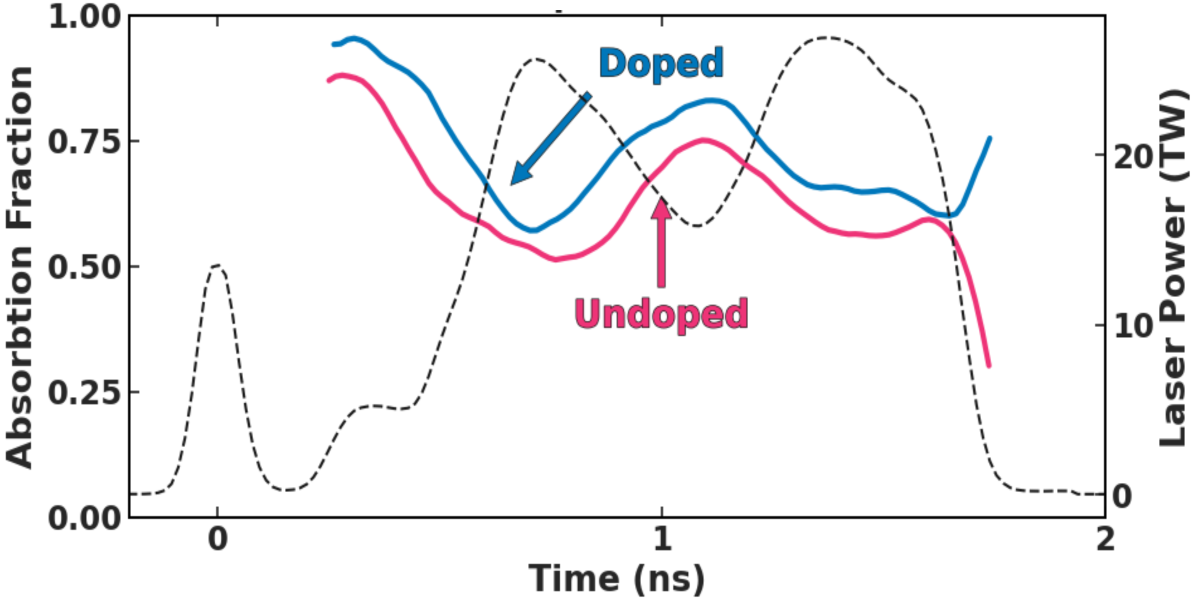
O Mannion et al, Phys. Plasmas 28, 042701 (2021)

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

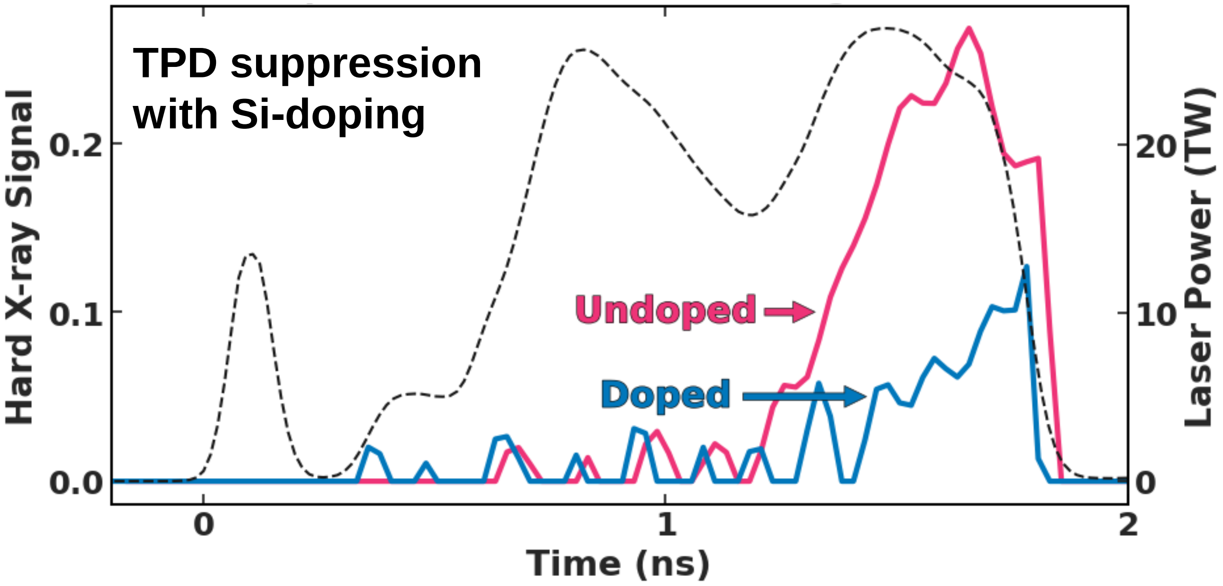


Shot 104949 (best performer, α_F=5)
Laser energy = 28.5 kJ
Yield = 2.1e14 (0.6 kJ)
ρR = 160mg/cm^2
χ(2.1MJ)≈0.85

Time dependent absorption

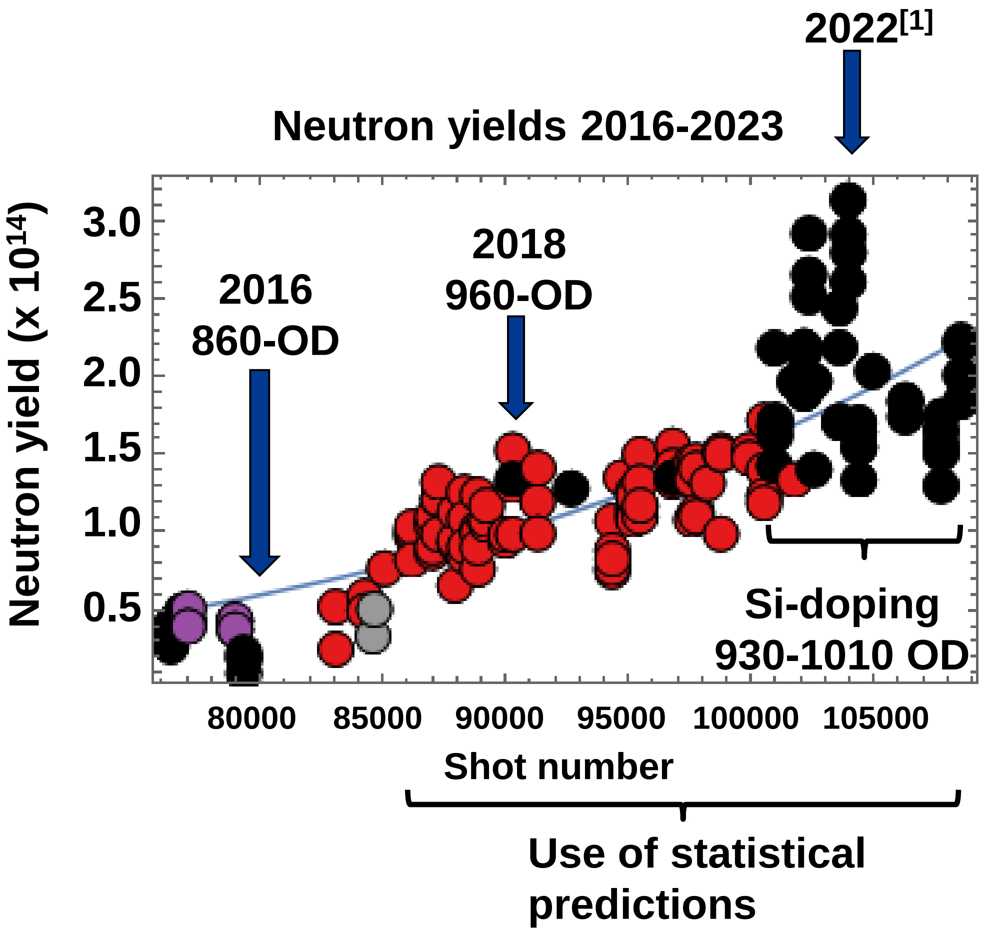


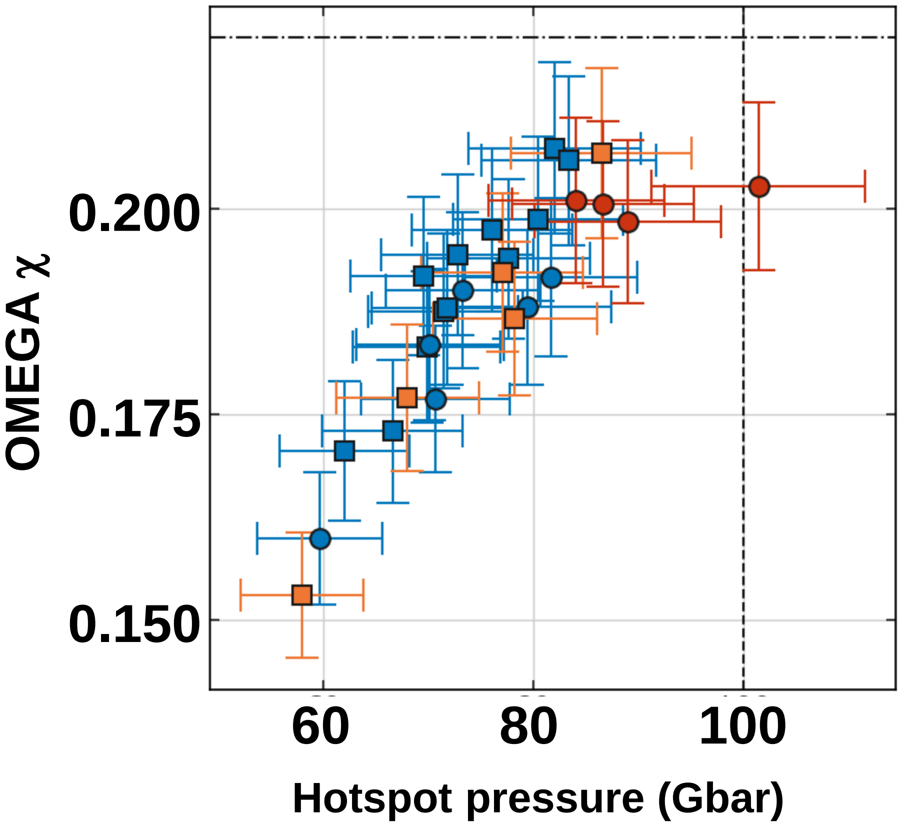
Hard X-ray signal from hot electrons (> 40keV)



Current performance metrics for OMEGA implosions

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

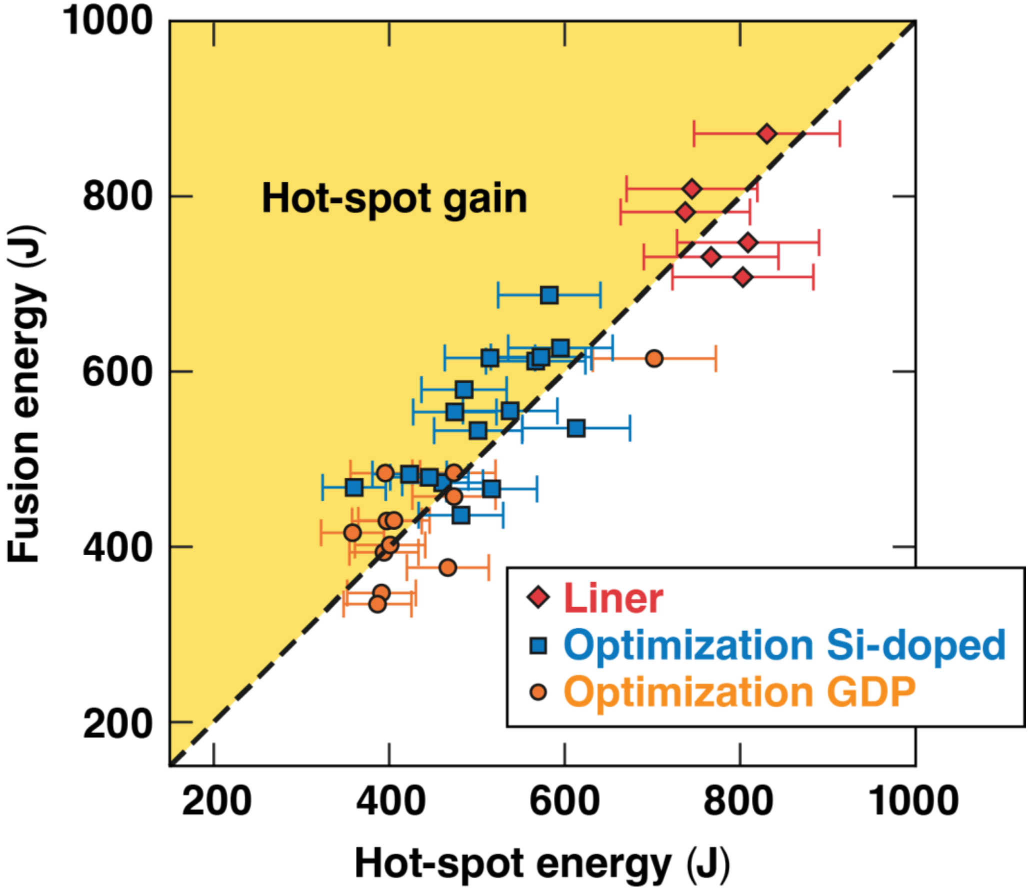




[1] Record yield achieved with high velocity DT liners (C. Williams PoP 2021)

Fusion energy outputs exceeding the internal energy of the fusing plasma were achieved on OMEGA (hotspot fuel gain > 1)

OMEGA experiments

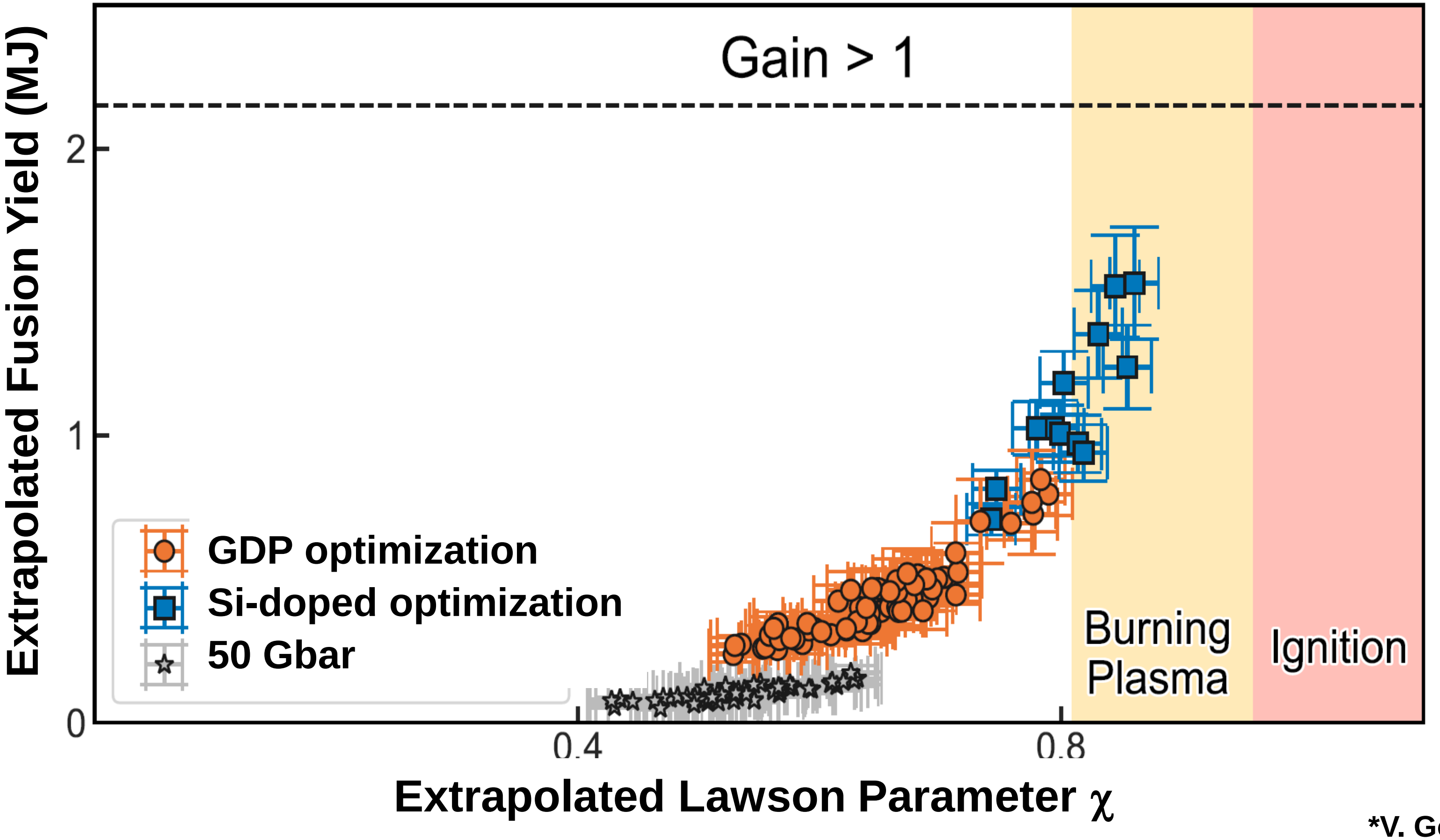


$Gain_{HS}$ =Fusion Energy/Hot-spot Energy at $R_{17}^{18keV\text{-}xray}$

C. Williams et al, submitted to Nature Physics

When hydrodynamically extrapolated to 2.1MJ of laser energy, the performance of OMEGA implosions is expected to enter the burning plasma regime

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



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

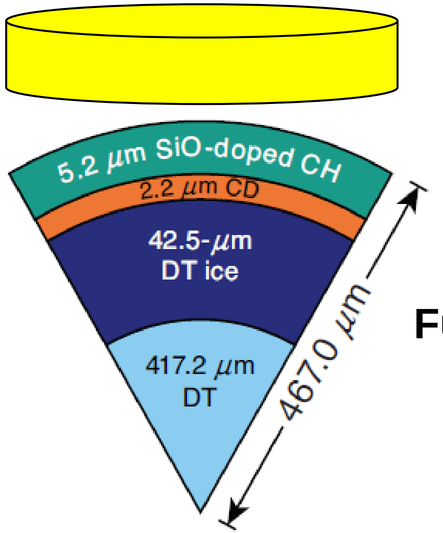
Uses 1D & 2D rad-hydro simulations and analytic models

*V. Gopalaswamy et al, submitted to Nature Physics

Upcoming implosion experiments in FY 24

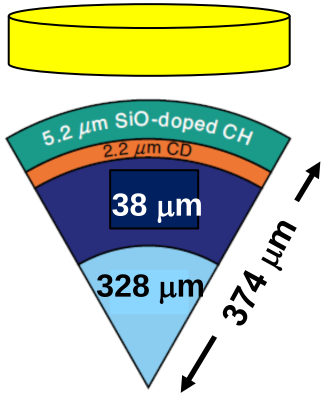
Optimization at smaller scale enables the exploration of a larger parameter space that includes higher intensities and higher ablation pressures

Beam diam 850µm

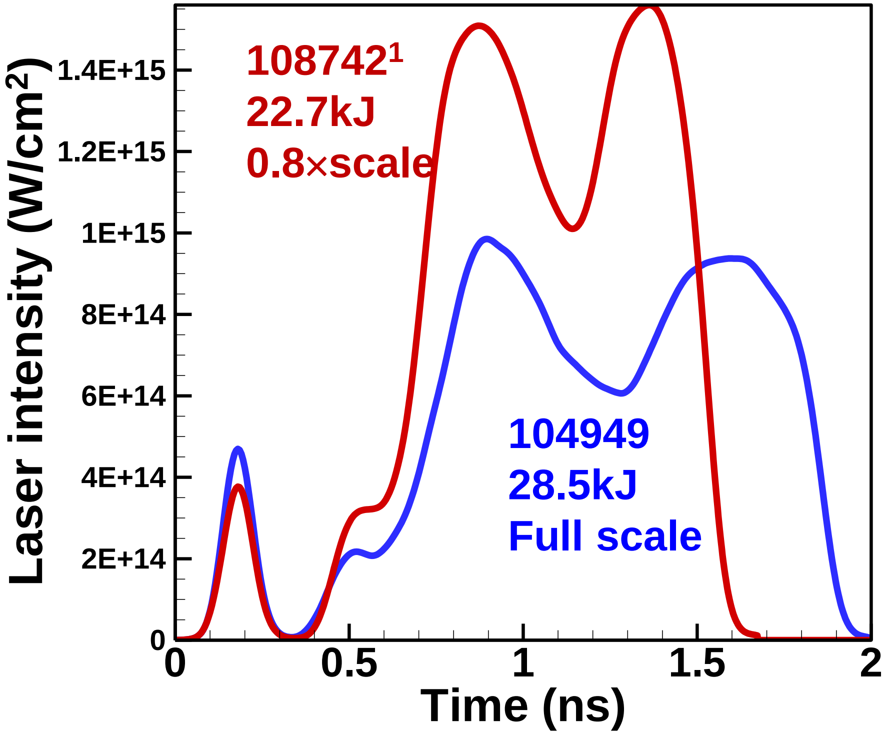


Full scale

Beam diam 650µm



0.8×scale



108742[1] - 0.8×scale
E_{laser} = 22.7kJ
Yield =1.4e14
Fill age = 8 days
$\chi(2.1MJ)_{adjusted}$=0.85

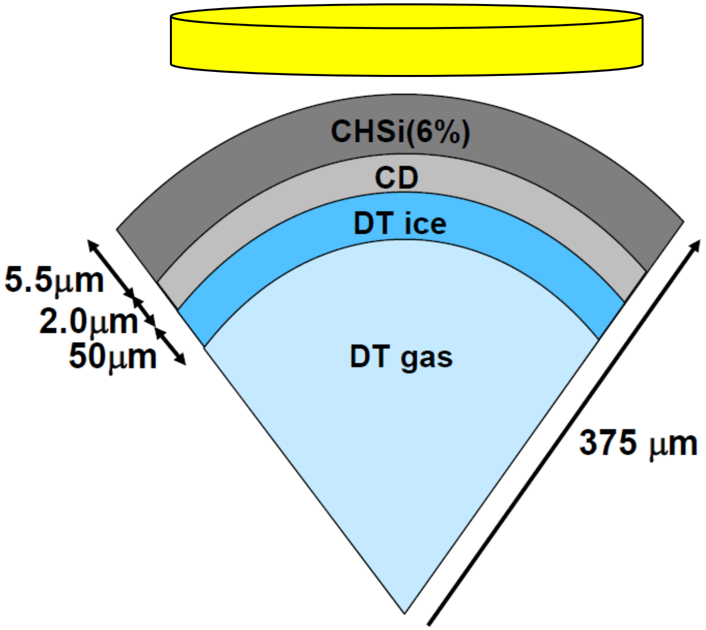
104949 – full scale
E_{laser} = 28.5kJ
Yield =2.1e14
Fill age = 3 days
χ(2.1MJ)=0.85

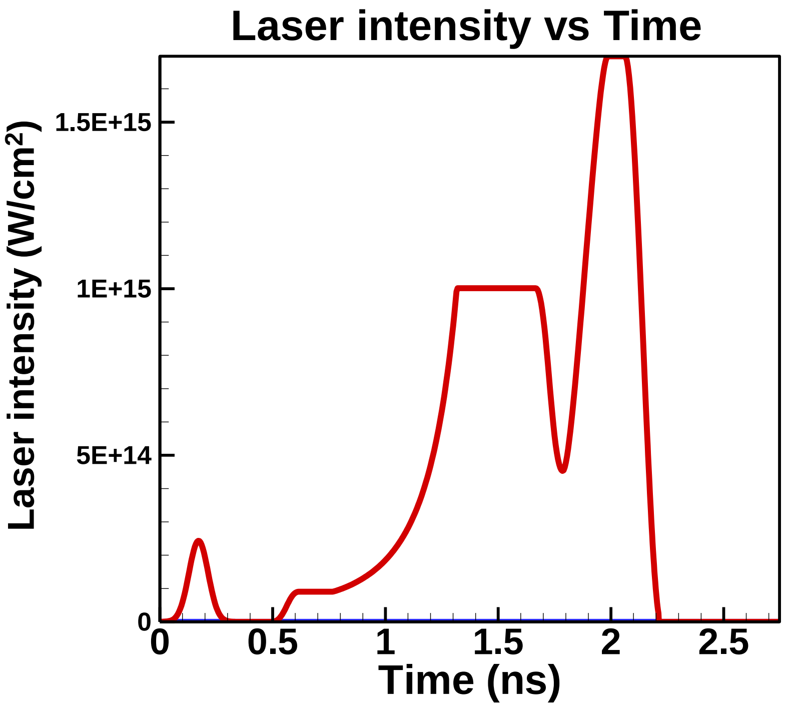
Initial optimization experiments at 0.8× scale[1] have reached the same scaled Lawson parameter as the full scale

[1] Experiments led by M. Rosenberg and C. Thomas (LLE)

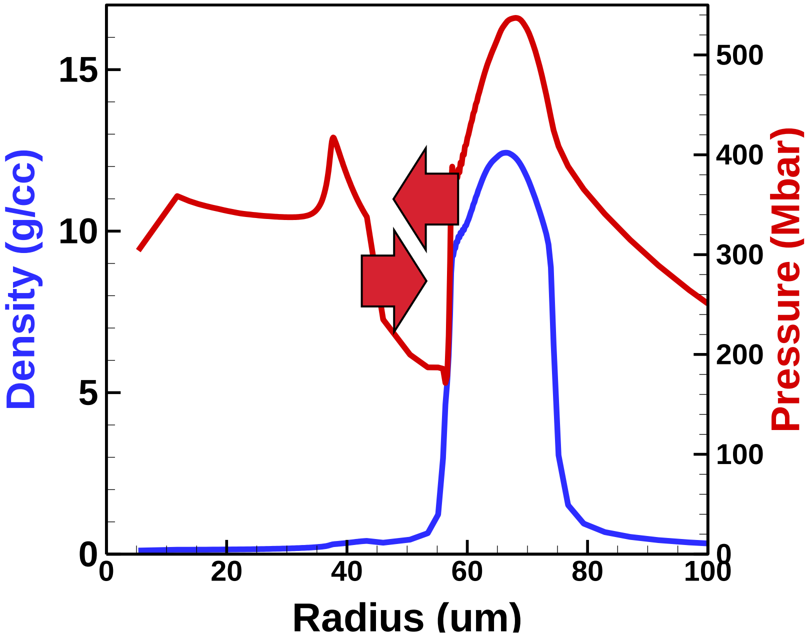
Shock-augmented[1] ignition designs[2] will be tested in FY24 using small 650μm beams to achieve high intensities in the shock-launching power-spike

Beam diam 650μm





Density and pressure at time of shock collision



DPP = distributed phase plates

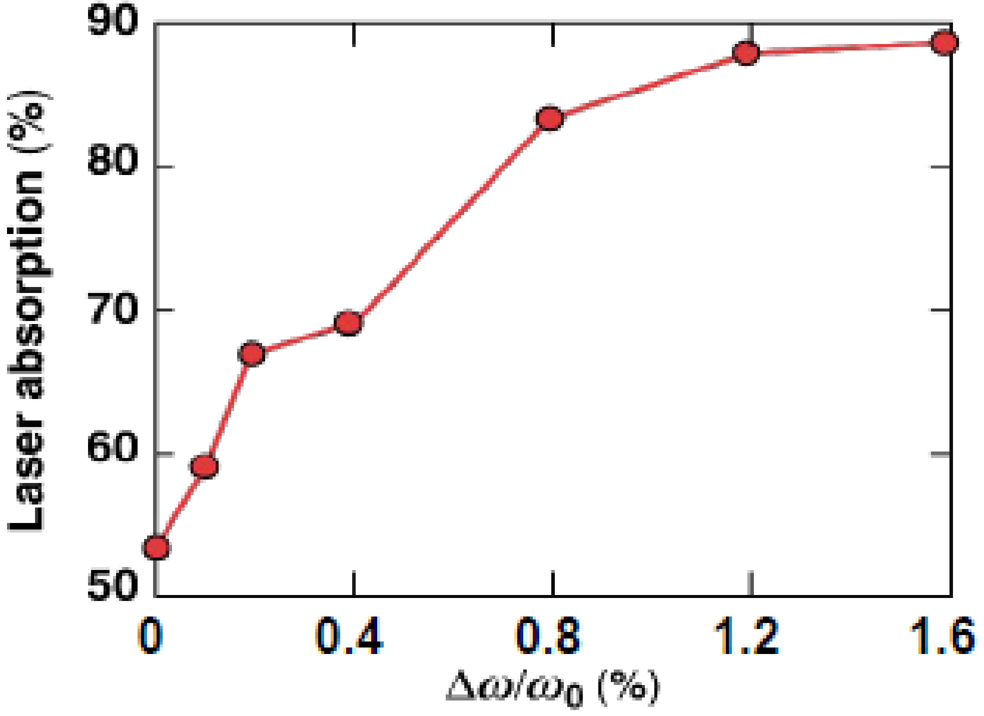
Shock pressures are still well below shock-ignition[3] requirements but statistical predictions indicate high values of the extrapolated Lawson parameter

[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)

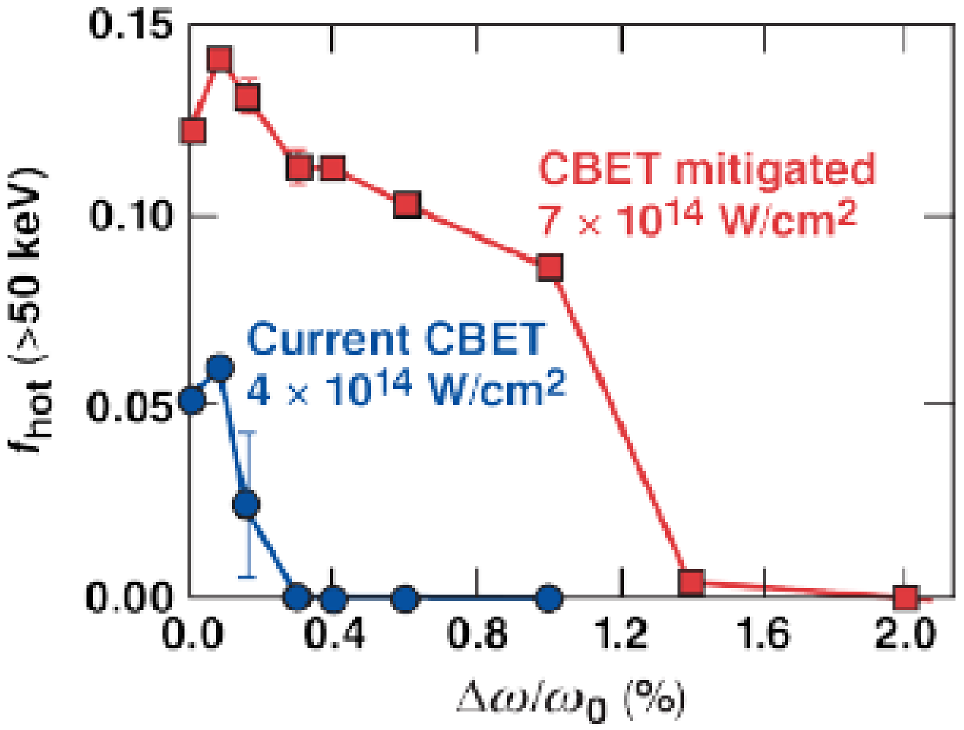
Future improvements: ultrabroadband lasers

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]

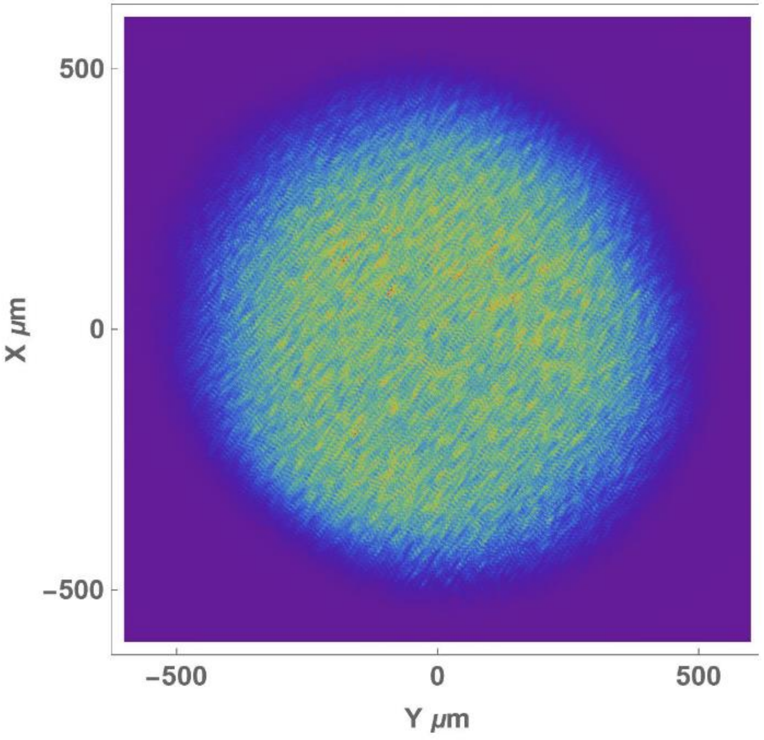


[1] R. Follet et al, Phys. Rev. Lett. 120, 135005 (2018)
[2] R. Follet al, Phys. Plasmas 28, 032103 (2021)

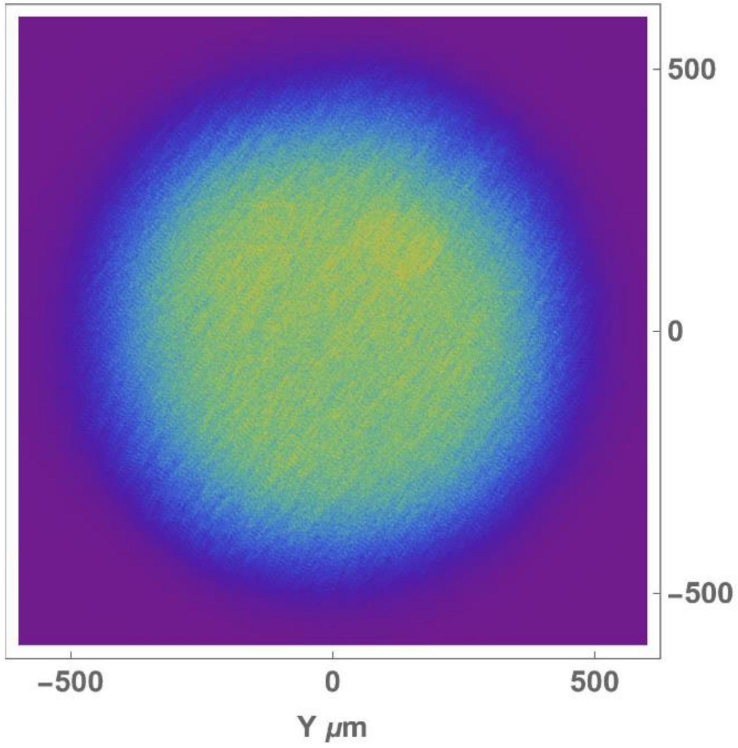
Greater laser bandwidth also reduces speckle amplitude and mitigates laser imprinting

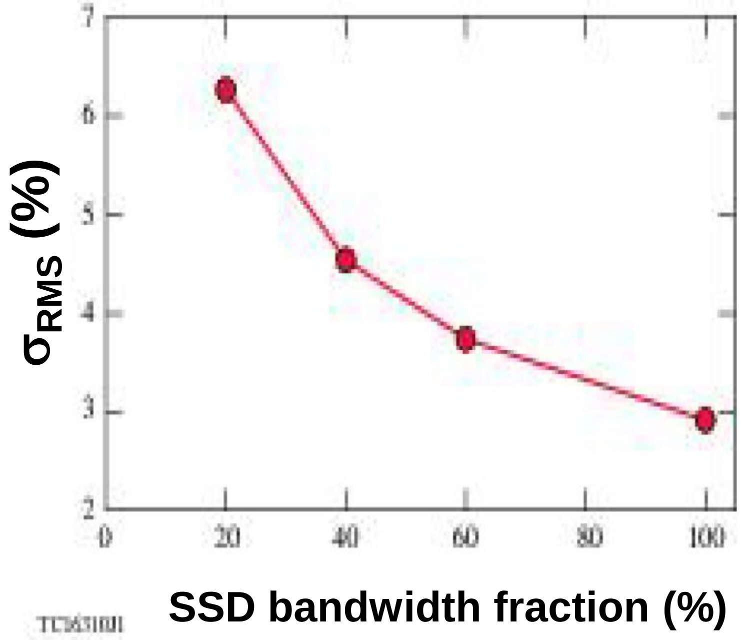
Current OMEGA 300 GHz SSD bandwidth
Measured far-field spatial laser intensity profiles

Beam profile at 20% bandwidth



Beam profile at 100% bandwidth





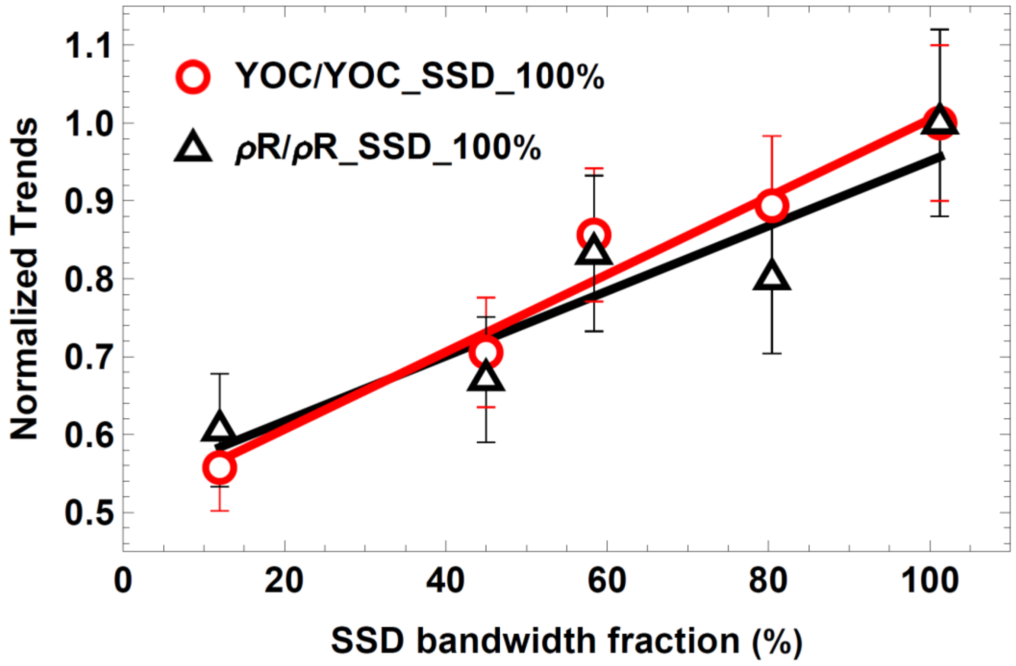
SSD = smoothing by spectral dispersion

At α_F=5, current high performers are insensitive to laser imprinting and SSD bandwidth. Dependency on bandwidth is observed at α_F=3.5

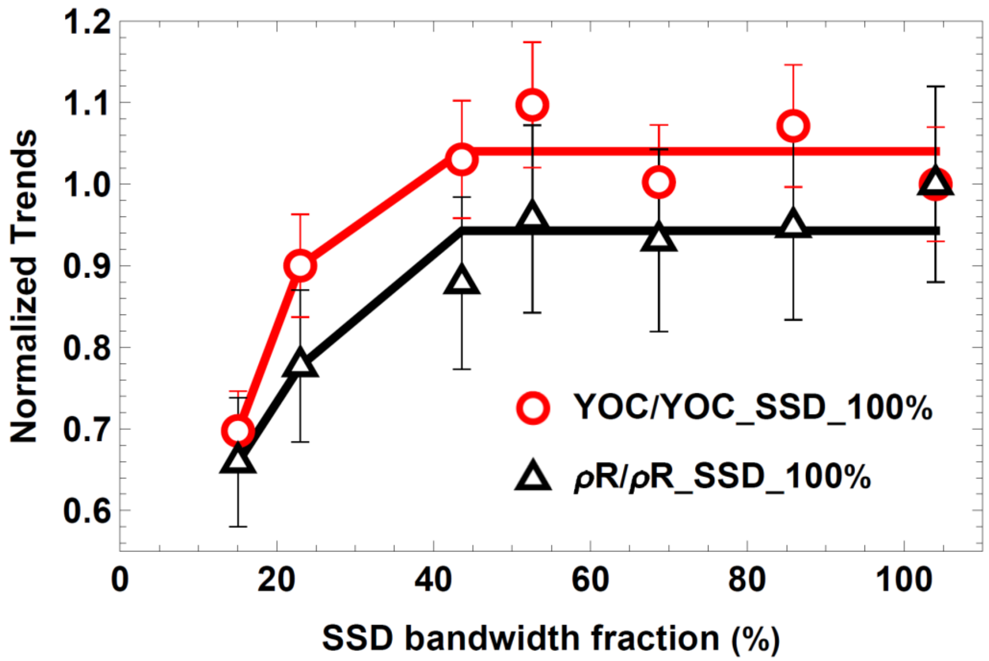
SSD = Smoothing by Spectral Dispersion

$$YOC \equiv \frac{Measured\,Yield}{Calculated\,Yield\,1D}$$

α_F = 3.5



α_F = 5



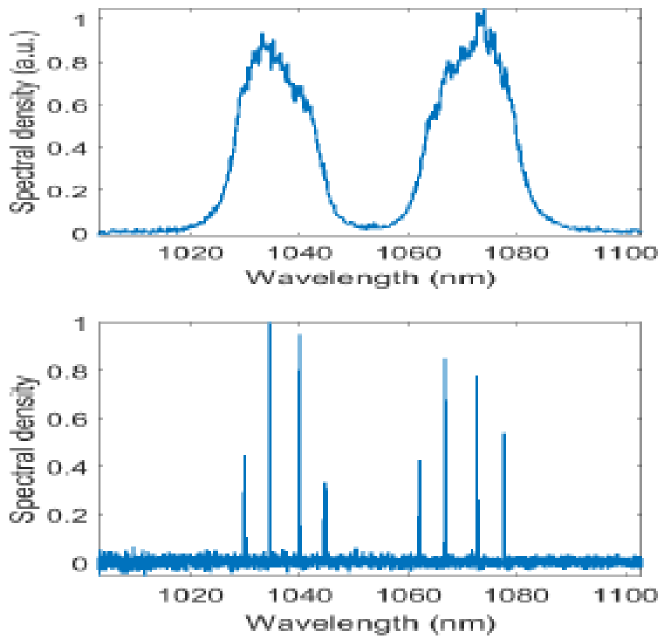
Higher laser bandwidth will enable performing low adiabat implosions

D. Patel, J. Knauer et al, Phys. Rev. Lett. 131, 105101 (2023)

The Fourth generation Laser for Ultrabroadband eXperiments (FLUX) will be commissioned next year and will use the OMEGA LPI platform to validate bandwidth modeling

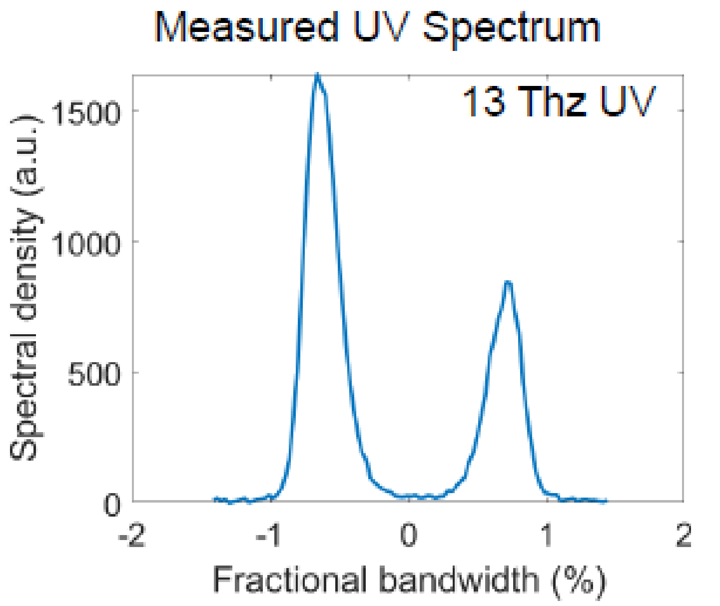
UR LLE

Ultrabroad Band Laser* (concept demonstration)



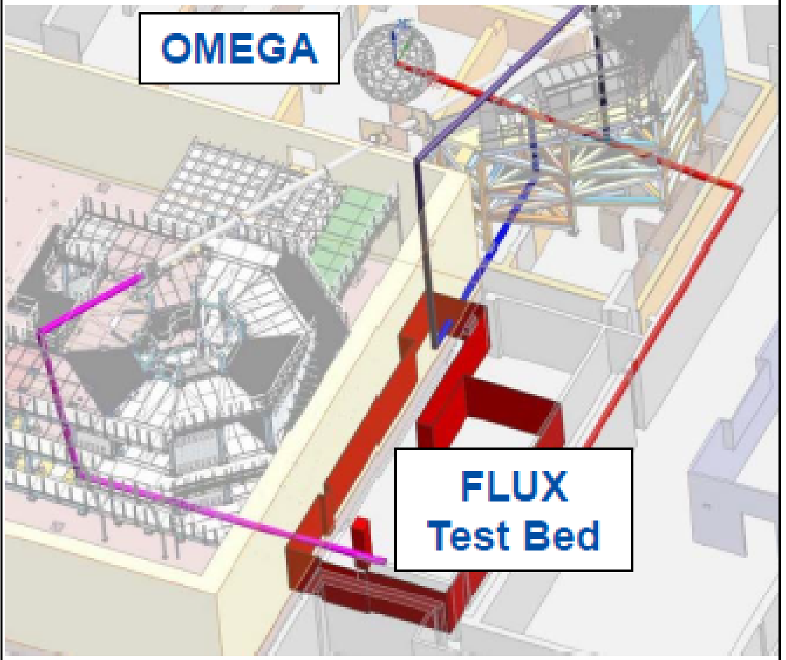
A colinear OPA was used to amplify broad bandwidth long-pulse laser beam

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)

Implosion experiments on OMEGA have achieved record Lawson parameters for direct drive and core conditions that scale to a burning plasma at NIF energies.

- Data-driven predictive models have been used to design high performance implosions on OMEGA
- The Lawson parameter has been improved by increasing coupled energy with larger, Si-doped targets and thinner ice layers
- When hydrodynamically extrapolated to 2.1 MJ of symmetric illumination, the best performing OMEGA implosions are expected to be in the burning plasma regime with a fusion yield of about 1.5 MJ
- Next generation broadband lasers are expected to improve energy coupling by mitigating laser plasma instabilities and reducing the seeds for hydrodynamic instabilities

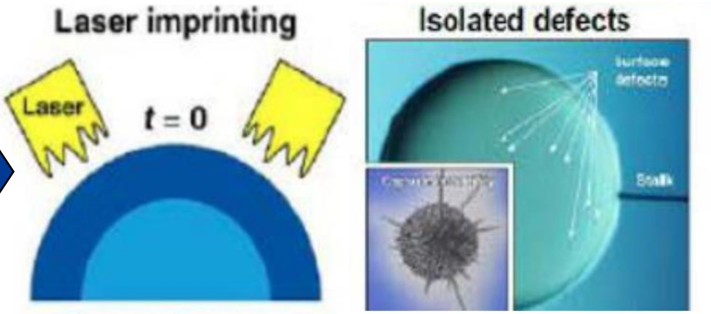
BACK UP SLIDES

Relevant dimensionless parameters are identified[1-3] that determine performance degradation in OMEGA implosions

Short wavelength Rayleigh-Taylor (RT)

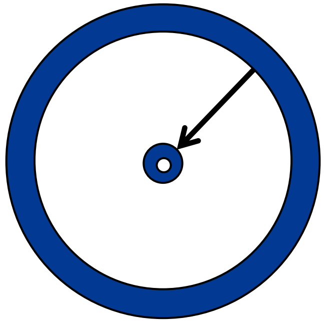
[4,5,6]

$$\frac{\alpha_F^{1.1}}{\mathrm{IFAR}}$$



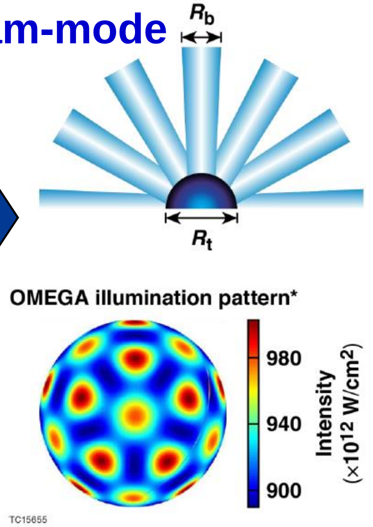
Convergence Ratio

$$\frac{R_0}{R_{HS}}$$



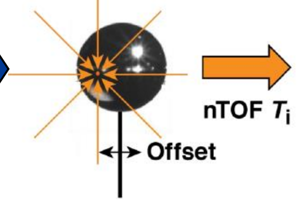
Beam-mode

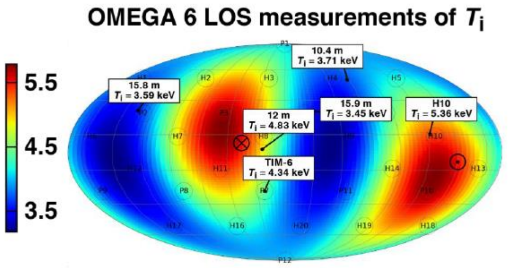
$$\frac{R_{beam}}{R_{target}}$$



Mode L=1

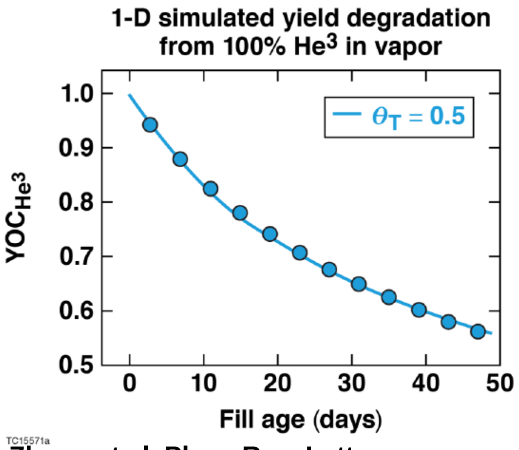
$$\frac{T_{max}}{T_{min}}$$





He^3 contamination from tritium decay

$$\mathrm{YOC}_{\mathrm{He3}}^{\mathrm{sim(1D)}}$$



[1] A. Lees et al, submitted to PoP (2022)
[2] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021
[3] V. Gopalaswamy et al, Phys. Plasmas 28, 122705 (2021)
[4] V. Goncharov et al, Phys. Plasmas 21, 056315 (2014)
[5] H. Zhang et al, Phys. Rev. Lett.
[6] H. Zhang et al, Phis. Plasmas 27, 122701 (2020)

A major goal for LLE is to produce scaled ignition conditions on OMEGA for direct drive. Hydrodynamic scaling is used to extrapolate OMEGA implosion performance to larger laser energies typical of the NIF

UR LLE

The measurable normalized ignition condition is determined by the Lawson parameter for ICF[1-4]

$$\chi_{\mathrm{exp}} = \frac{nT\tau}{[nT\tau]_{ign}} \sim \left[(\rho R)^2 \left(\frac{Y_{DT}}{M_{DT}}\right)\right]^{1/3}$$

The Lawson parameter increases linearly with scale, giving the condition for scaled ignition

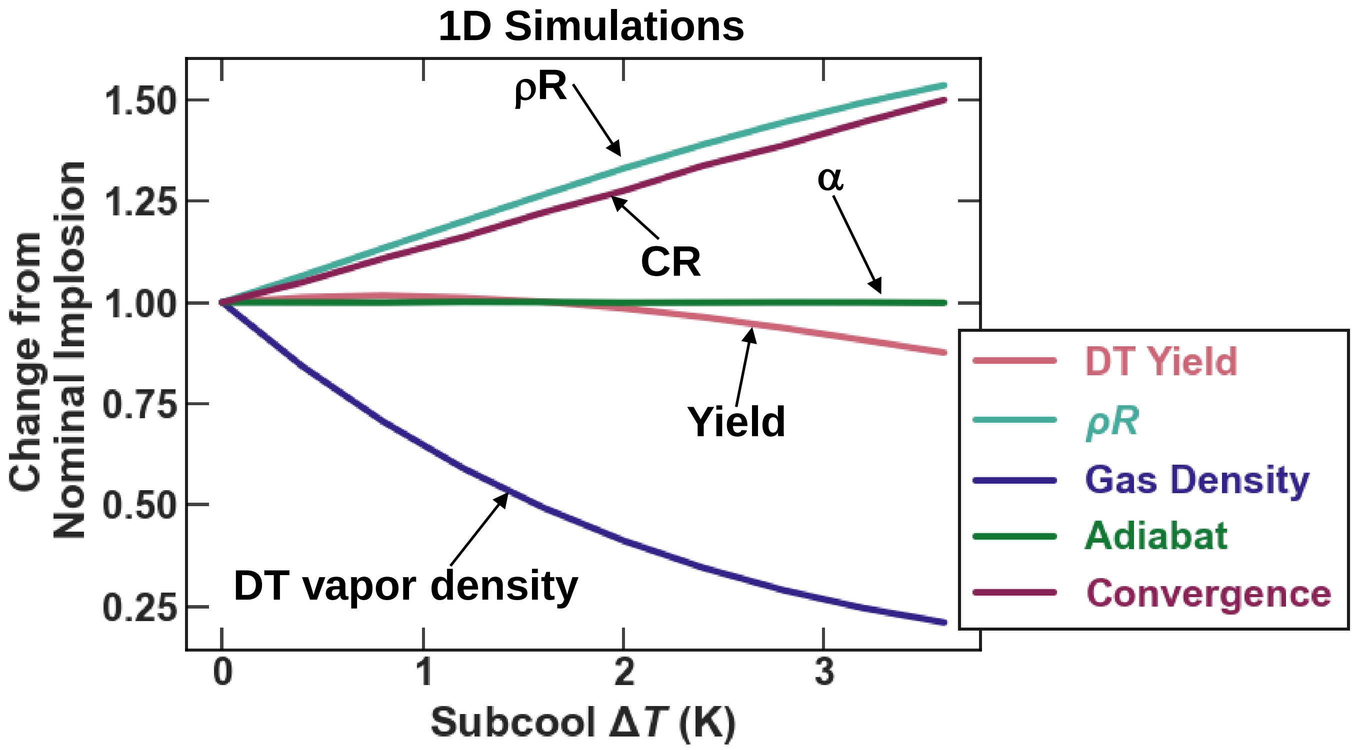
$$\chi_{\mathrm{scaled}} \sim \tau \sim R \sim E_{Laser}^{1/3} \quad \Rightarrow \quad \chi_{\mathrm{scaled}} \equiv \chi_{\mathrm{OMEGA}} \left(\frac{E_L^{\mathrm{scaled}}}{E_L^{\mathrm{OMEGA}}}\right)^{1/3} > 1$$

Hydroequivalent Ignition is $\chi = 1$ at NIF energies of 2.1 MJ

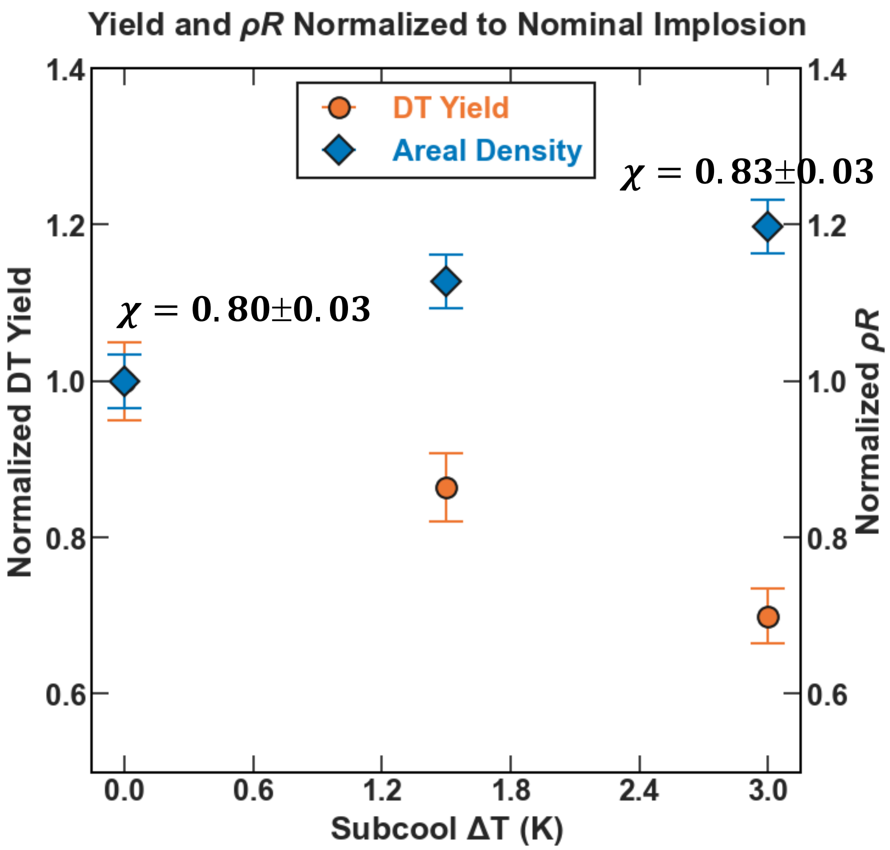
[1] A. Christopherson et al, Phys. Plasmas 27, (2020)
[2] R. Betti et al, Phys. Rev. Lett. 114, 255003 (2015)
[3] J. D. Lindl et al. Phys. Plasmas 25, 122704 (2018)
[4] B.K. Spears et al, Phys. Plasmas 19, 056316 (2012)

Initial experiments show that ρR and CR increase with subcooling while the fusion yield decreases. Overall impact points to higher Lawson parameter

Subcooling below the triple point leads to higher convergence without changes to the adiabat



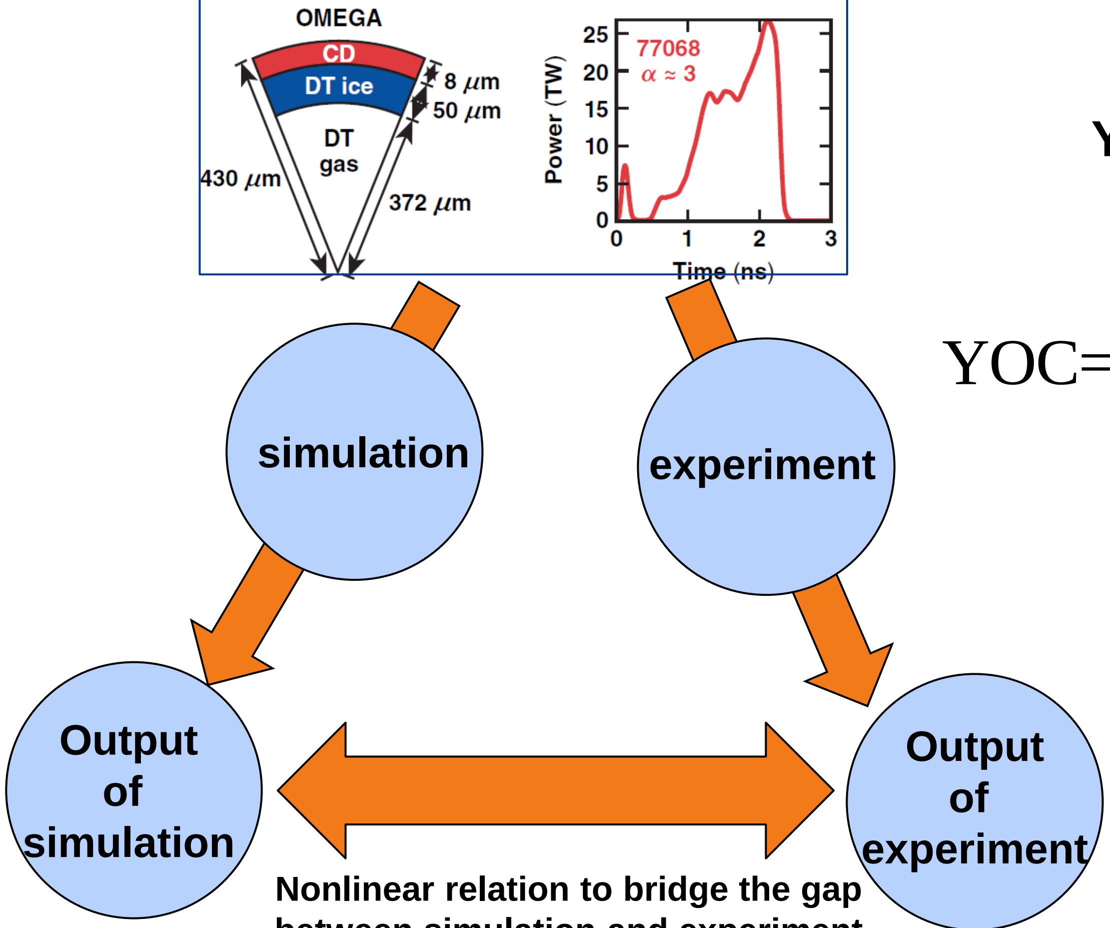
Initial experiments



Experiments by J. Knauer,
L. Ceurvorst and V. Gopalaswamy

Statistical mapping or DNN can be used to bridge the gap between simulations and experiments to develop a predictive capability and understand degradation sources

Laser pulse and target specifications are inputs to both the code and the experiment



Nonlinear relation to bridge the gap between simulation and experiment

$$\text{YOC= Yield Over Clean} = \frac{\text{Yield measured}}{\text{Yield 1D simulation}}$$

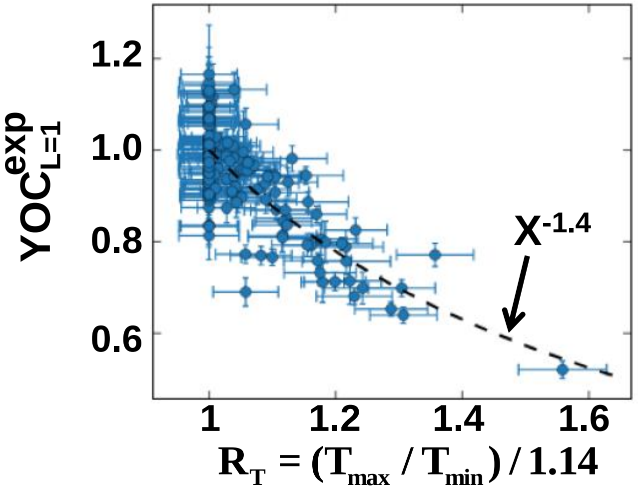
$$YOC = YOC_{stab}(\alpha, IFAR, CR)\, YOC_{beam}\left(\frac{R_b}{R_t}\right) YOC_{L=1}\left(\frac{T_{max}}{T_{min}}\right)\ldots$$

[1] V. Gopalaswamy et al, Nature 565, 581-586 (2019)
[2] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021)

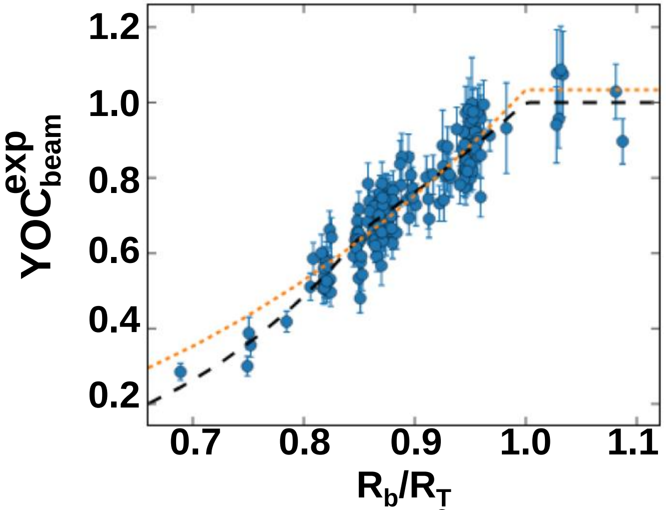
33

Each degradation mechanism can be isolated and quantified[1]

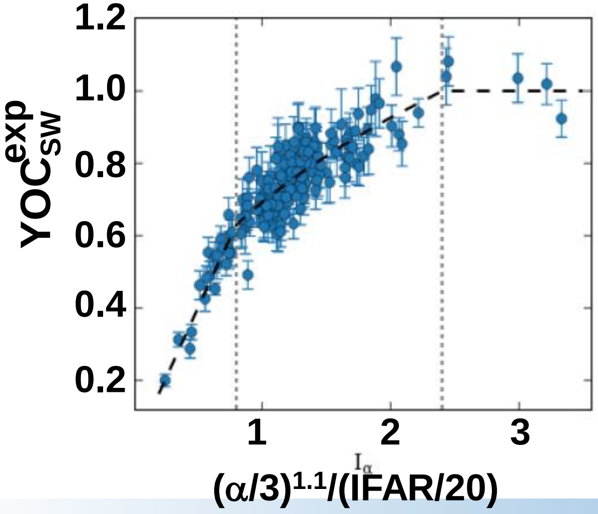
Degradation from mode L=1



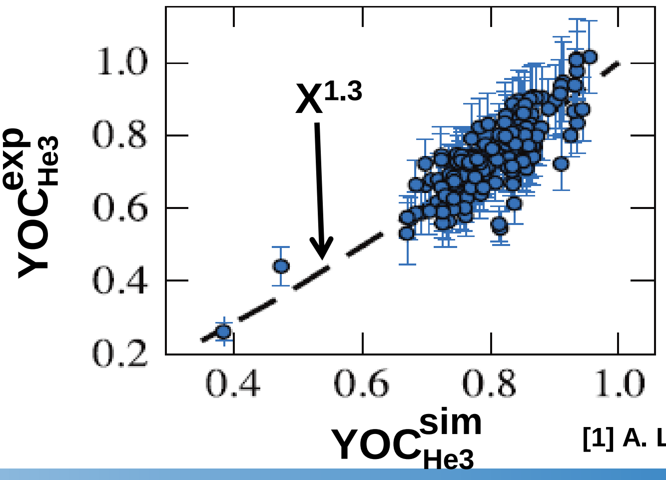
Degradation from beam mode



Degradation from short wavelength RT

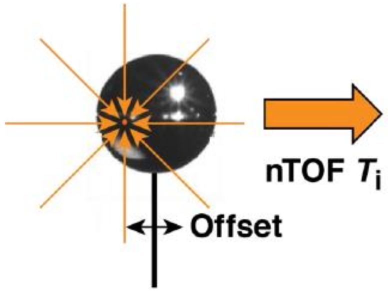


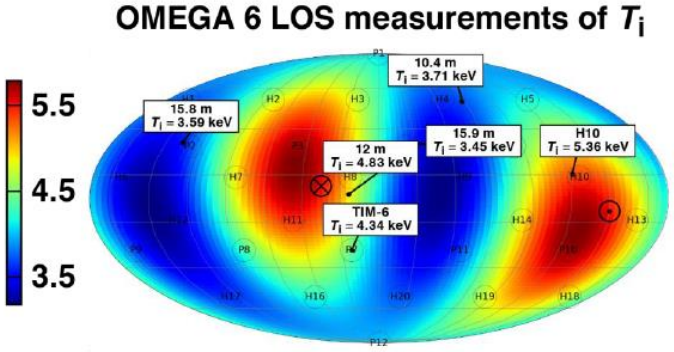
Degradation from He^3 accumulation



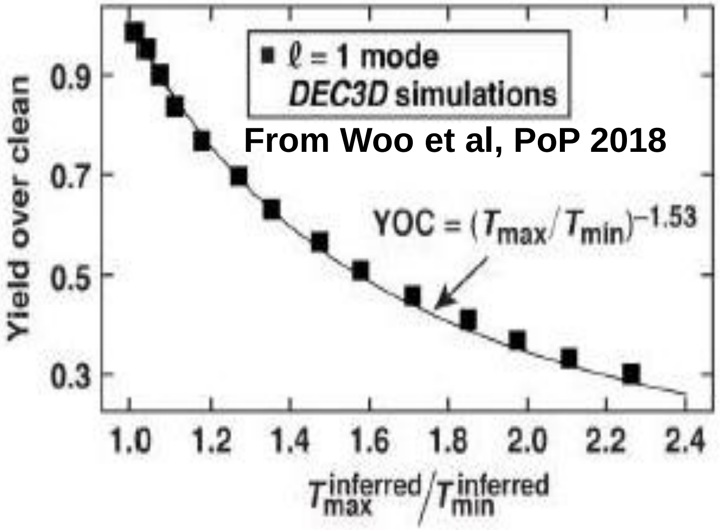
[1] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021)

The effects of mode L=1 from offset and mispointing are assessed through the measured T_i asymmetries

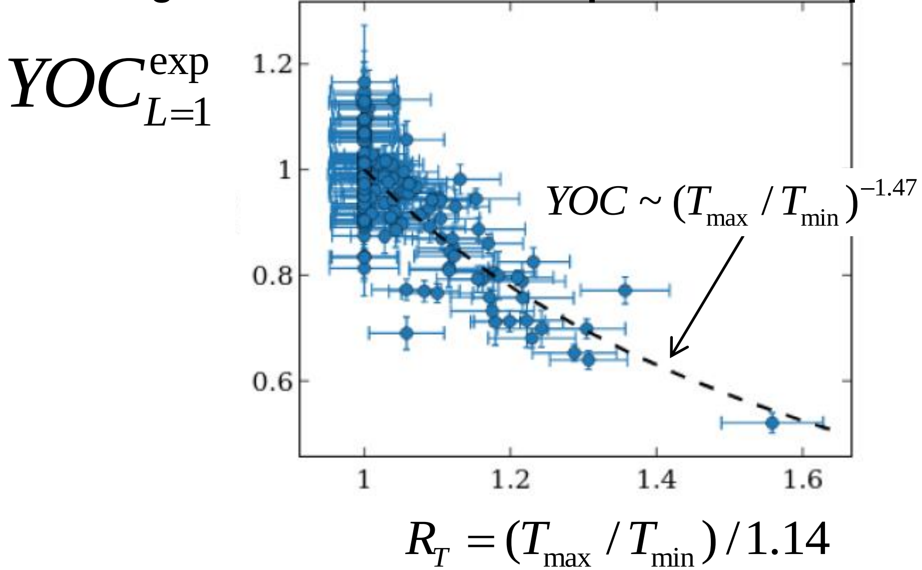




Degradation from L=1: Simulated dependence



Degradation from L=1: Experimental dependence

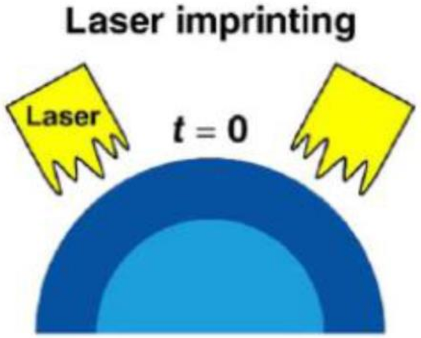


The SM uses mapping of experimental data onto simulated dimensionless parameters[1-3] determining performance degradation

Short wavelength Rayleigh-Taylor (RT)

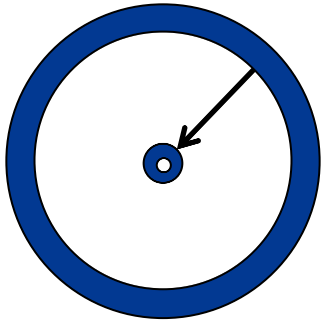
[4,5,6]

$$S = \frac{\alpha_F^{1.3}}{IFAR}$$



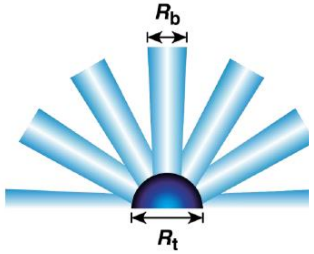
Convergence Ratio

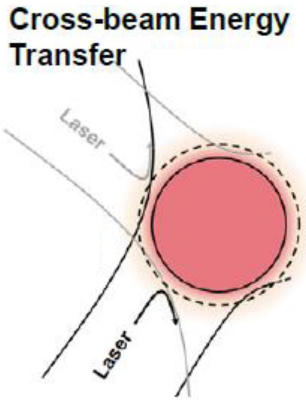
$$CR = \frac{R_0}{R_{HS}}$$

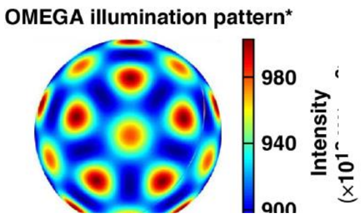


Beam-mode and CBET

$$\frac{R_{beam}}{R_{target}}$$

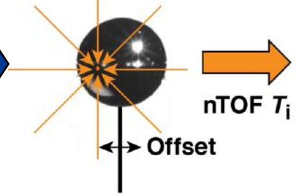


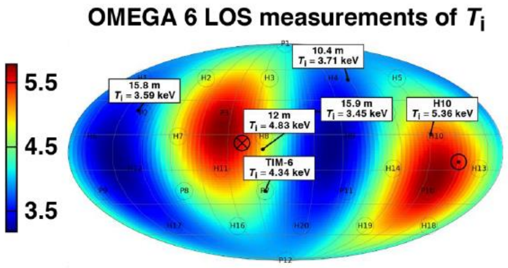




Mode L=1

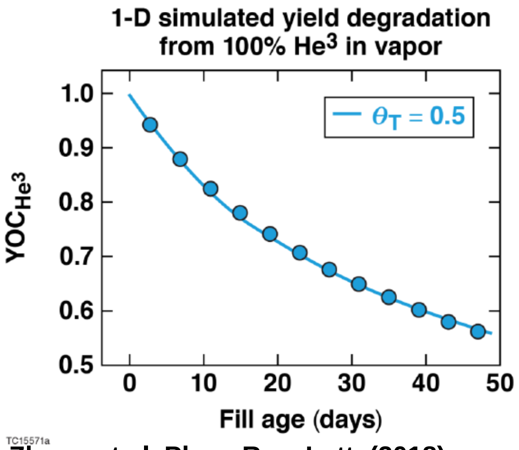
$$\frac{T_{max}}{T_{min}}$$





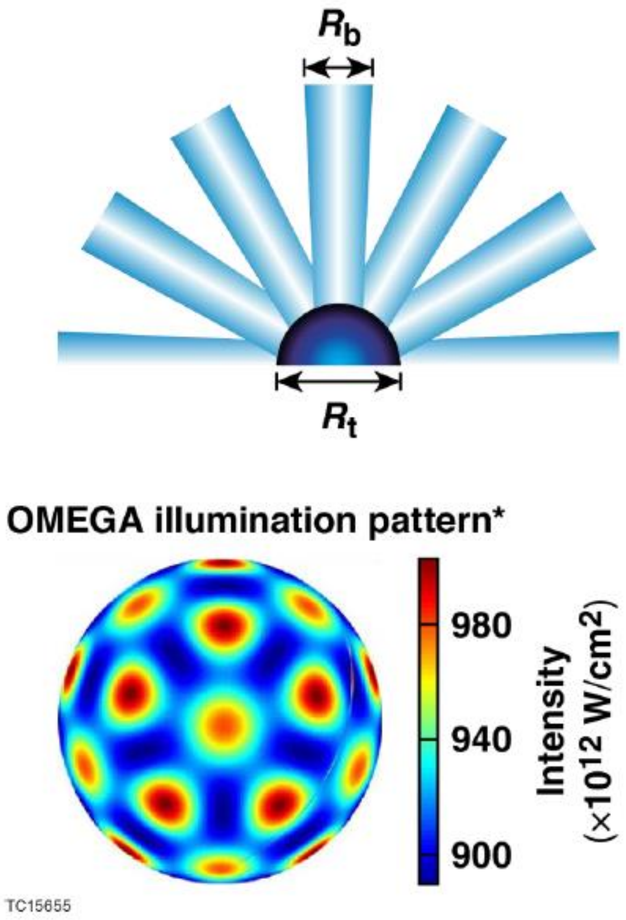
He[3] contamination from tritium decay

$$YOC_{He3}^{sim(1D)}$$

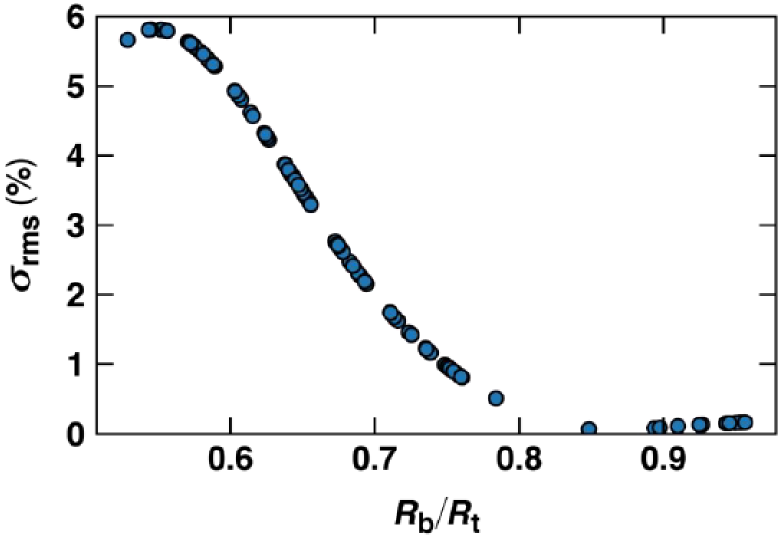


[1] A. Lees et al, submitted to PoP (2022)
[2] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021
[3] V. Gopalaswamy et al, Phys. Plasmas 28, 122705 (2021)
[4] V. Goncharov et al, Phys. Plasmas 21, 056315 (2014)
[5] H. Zhang et al, Phys. Rev. Lett. (2018)
[6] H. Zhang et al, Phis. Plasmas 27, 122701 (2020)

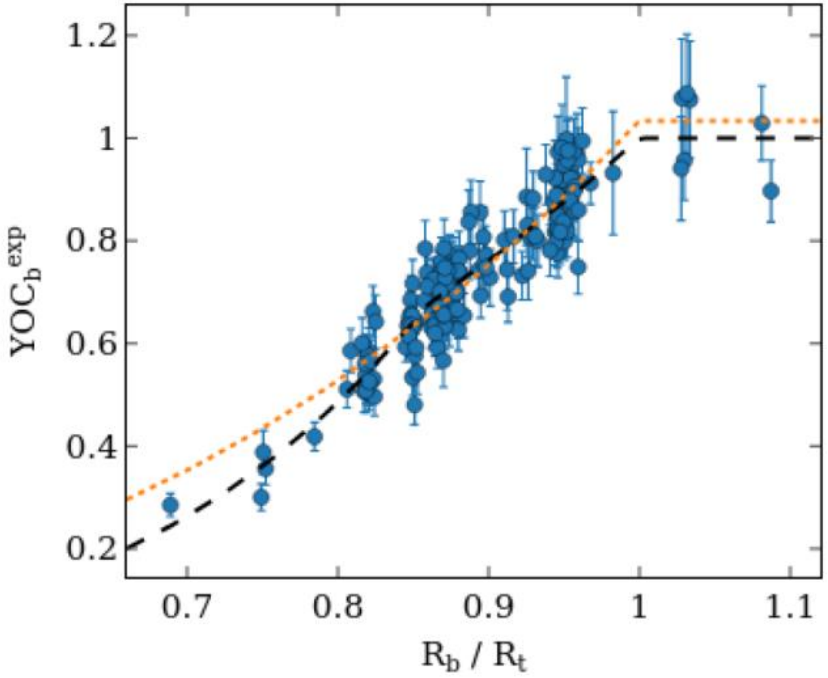
The fusion yield is reduced by the ratio of the laser beam to target radius indicating degradation from laser illumination nonuniformities from port geometry



Hard sphere illumination nonuniformity is closely related to R_b/R_t



Degradation from beam mode: experimental dependence



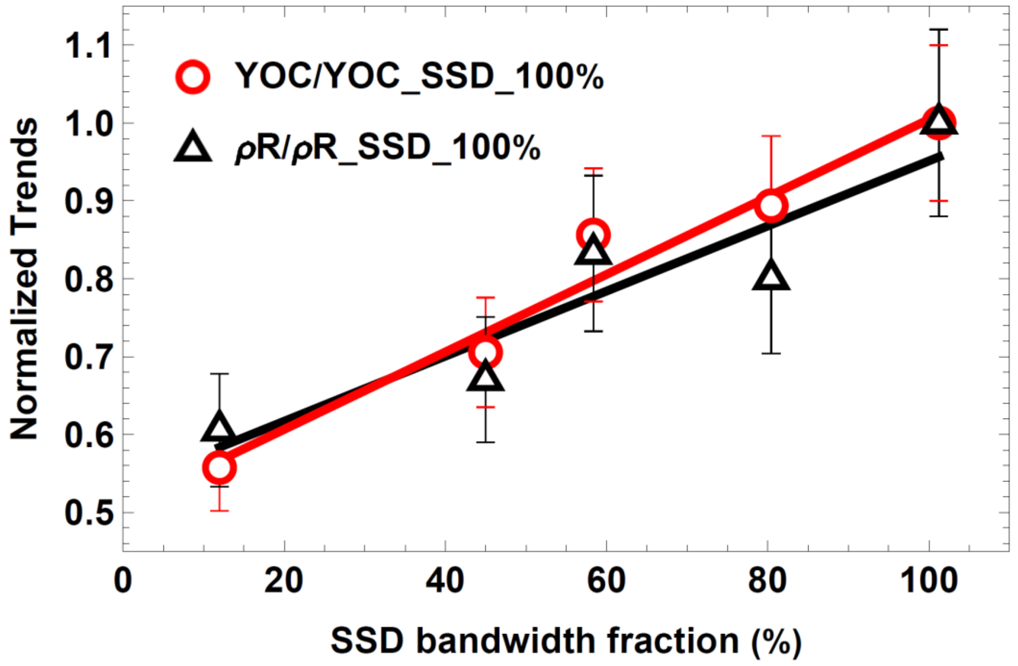
See also A. Colaitis et al, PRL 2022

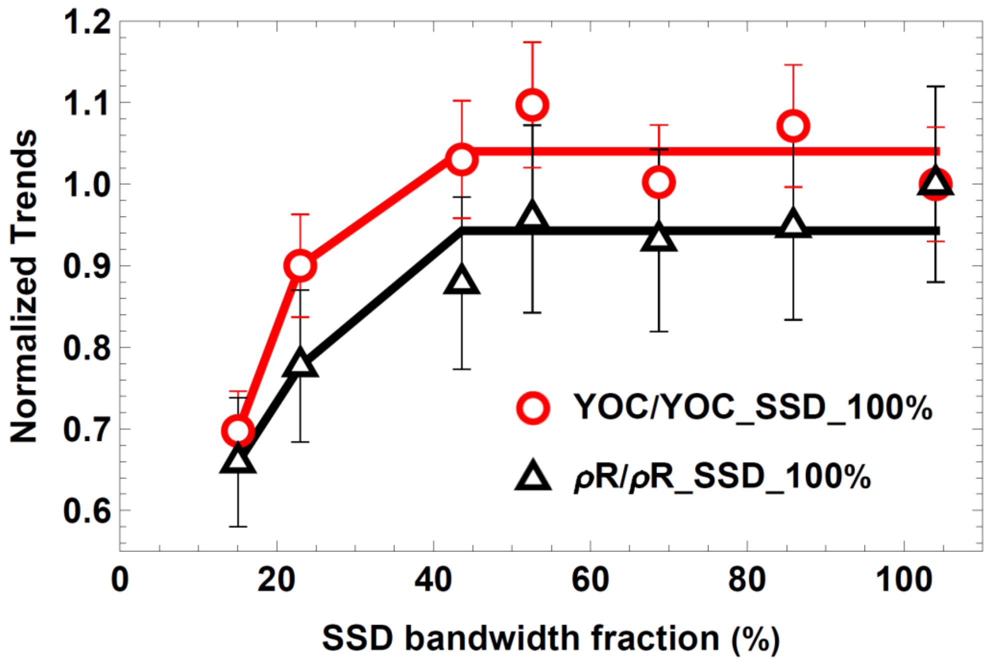
Laser bandwidth is a dominant lever for mitigating imprinting in low α_F targets. At α_F=5, current high performers are insensitive to bandwidth

$\alpha = 3.5$

$$YOC \equiv \frac{Measured\ Yield}{Calculated\ Yield\ 1D}$$

$\alpha = 5$



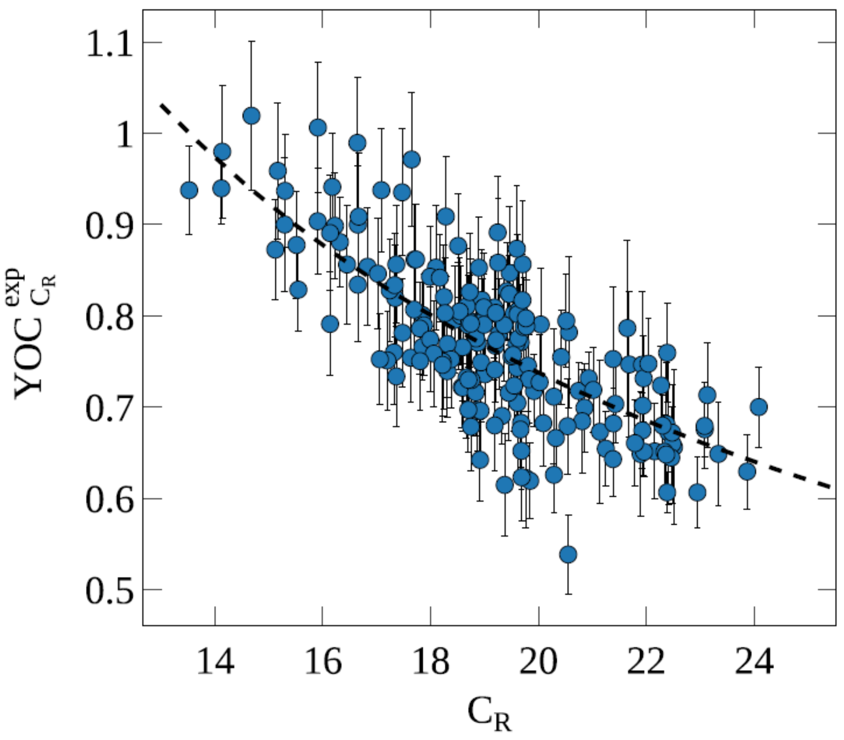


D. Patel, in press in PRL

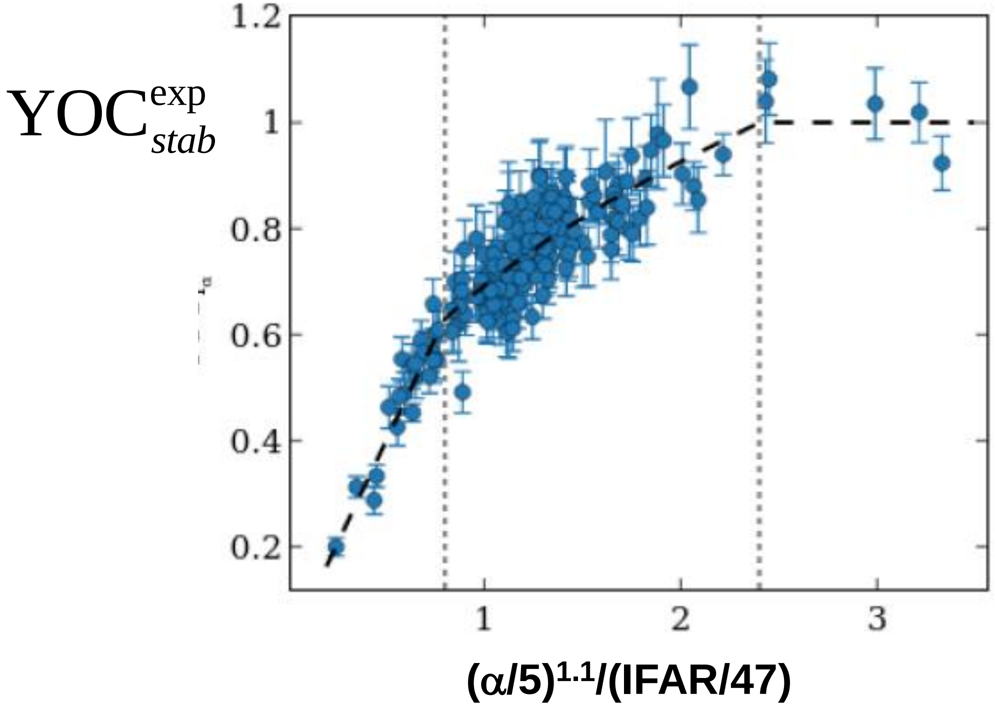
Higher laser bandwidth will enable performing low adiabat implosions

The fusion yield is reduced by short-wavelength Rayleigh-Taylor (probably seeded by laser imprinting) and low and/or mid modes from the laser

Degradation from low or mid modes



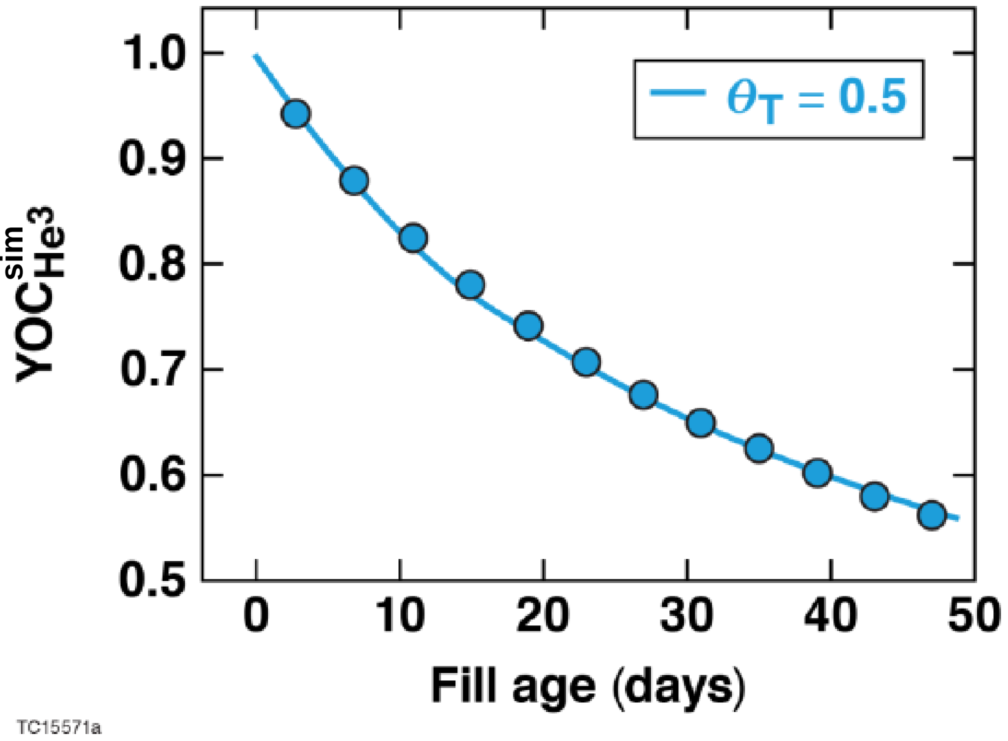
Degradation from short wavelength hydro instabilities: experimental dependence



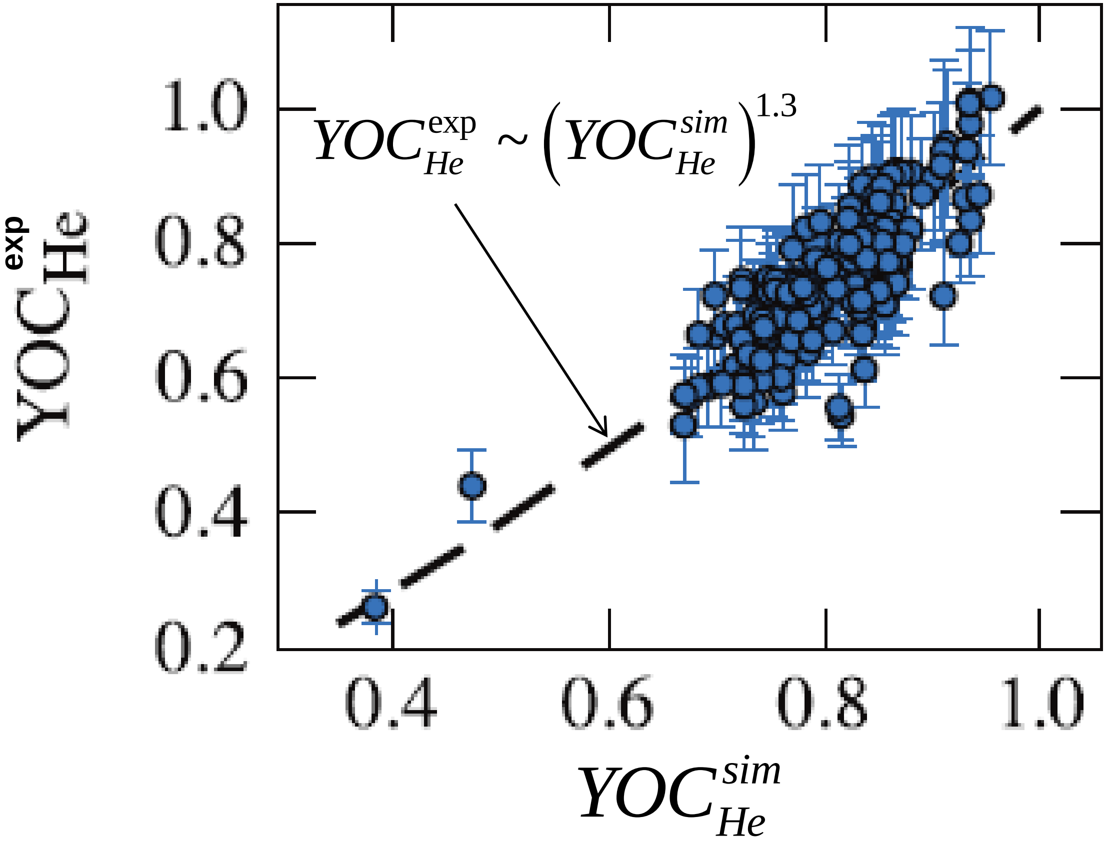
* V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).
H. Zhang *et al.*, Phys. Plasmas 27, 122701 (2020).
RT: Rayleigh–Taylor
IFAR: in-flight aspect ratio

He^3 produced from tritium decay accumulates in the DT vapor over time leading to fusion yield degradation

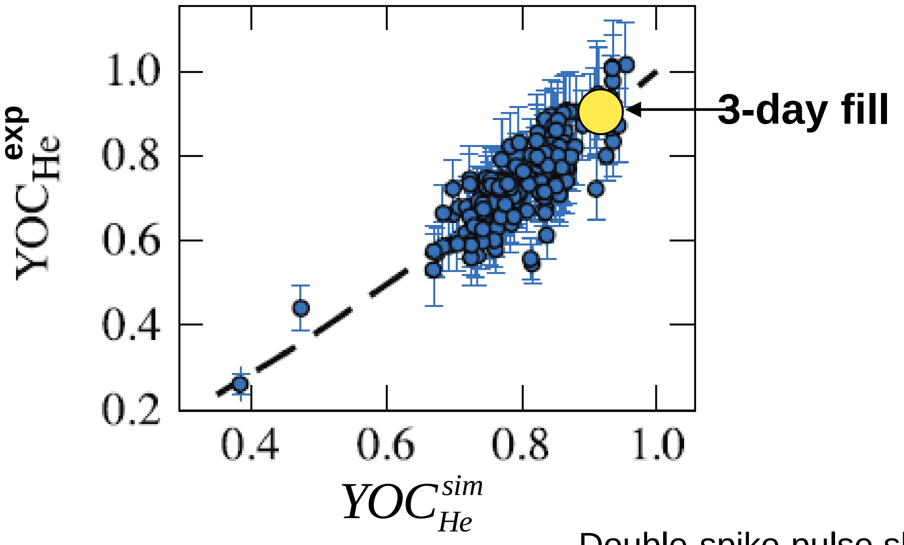
He^3 degradation:
simulated dependence from 100% He^3 in vapor

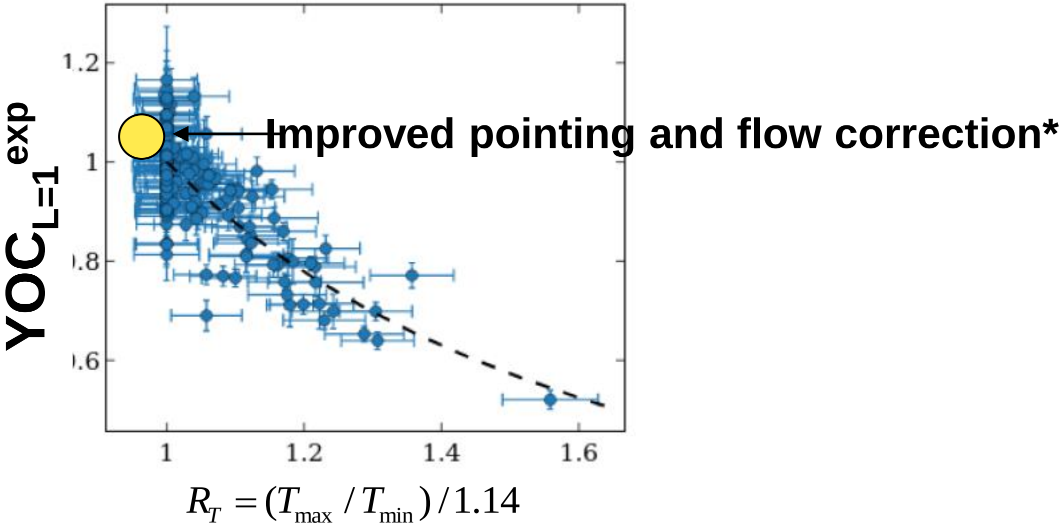


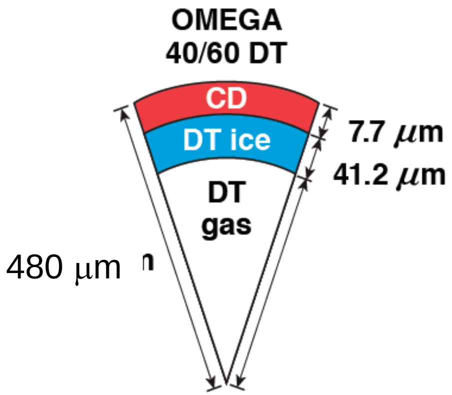
He^3 degradation:
experimental dependence

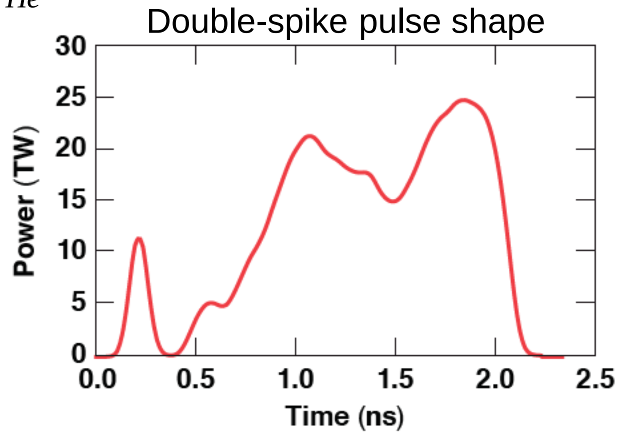


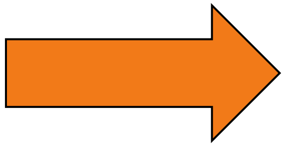
Implosions were optimized with respect to: pulse shaping, He^3 accumulation and L=1 suppression using target offsets to compensate for laser mispointing









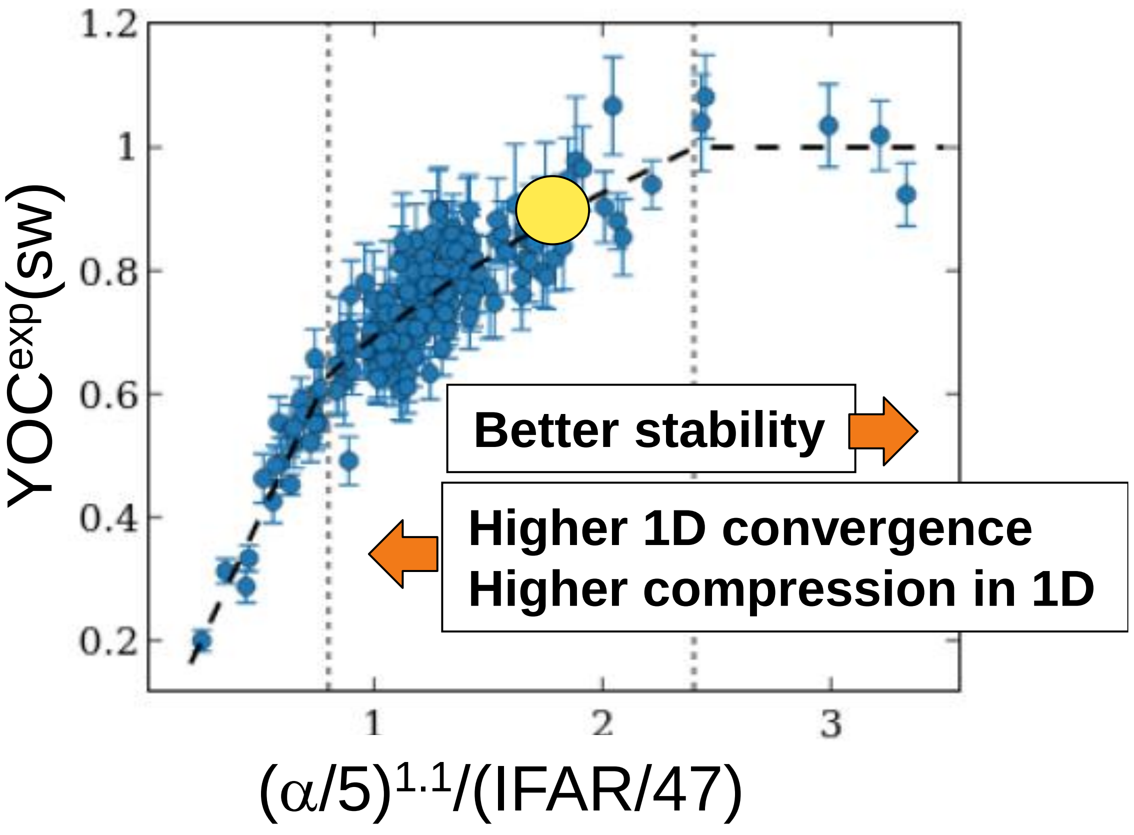


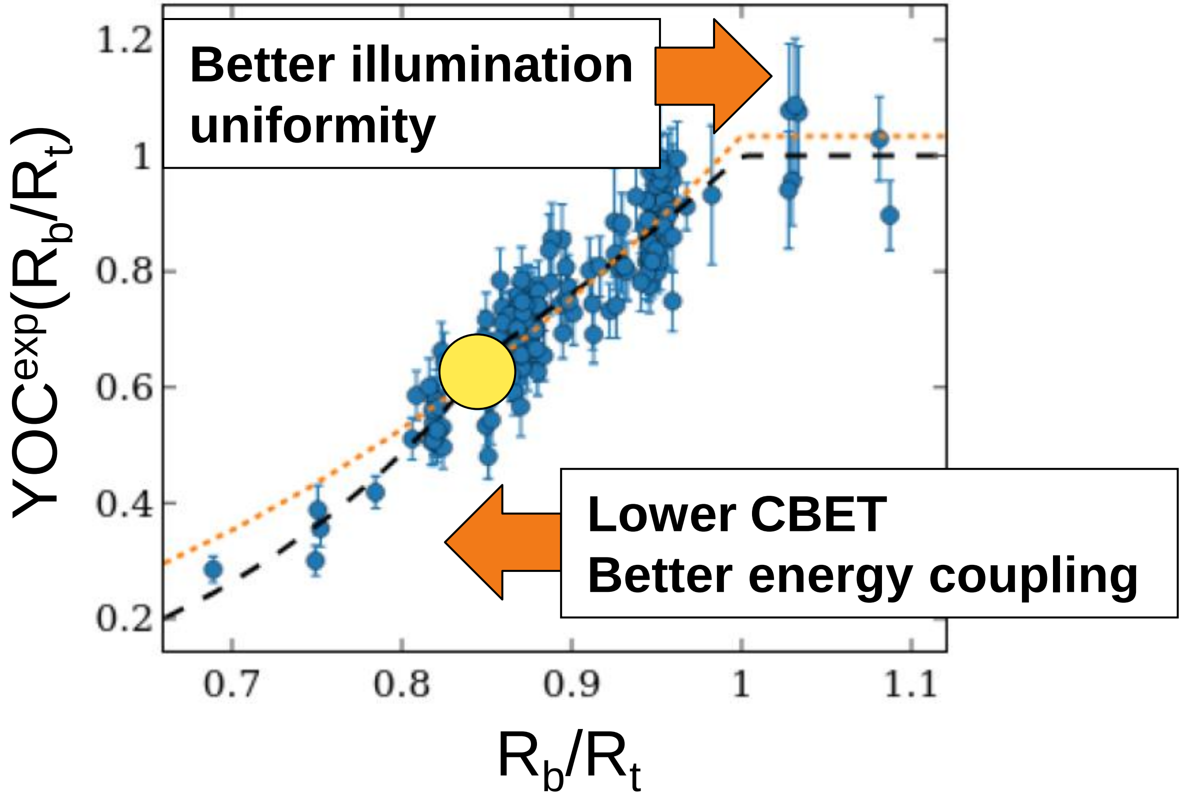
Shot 99922, 90288
Yield = 1.57e14
ρR = 160mg/cm²
χ(2MJ)≈0.74

***O. Mannion, PoP (2021)**

Implosions were also optimized with respect to: hydrodynamic stability, 1D performance, laser beam mode degradation and CBET reduction

→ optimum

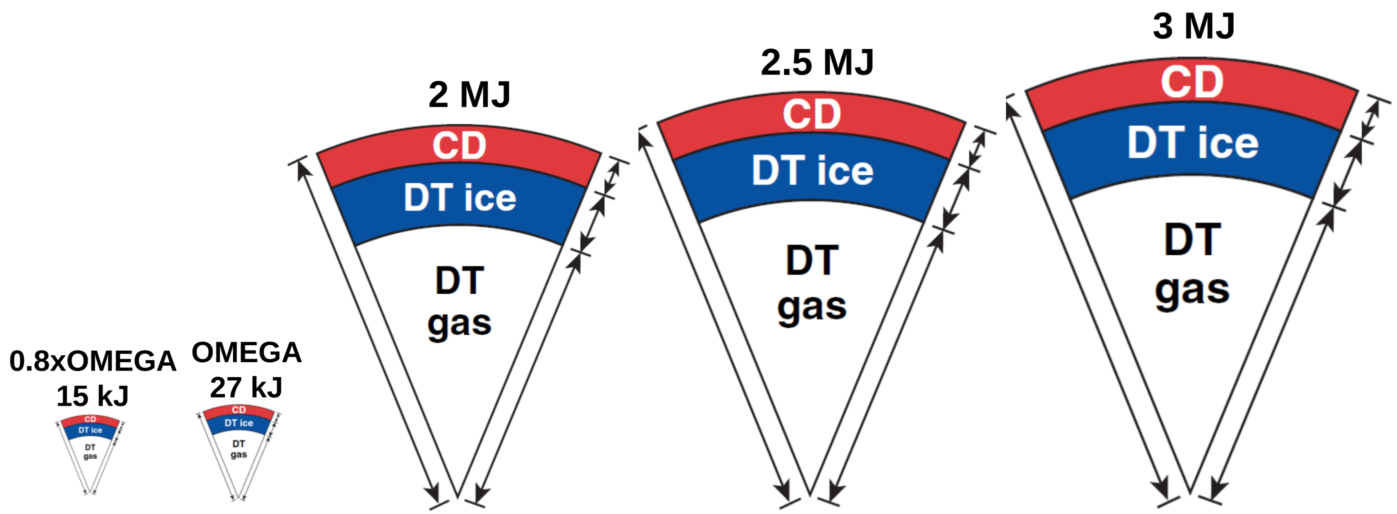




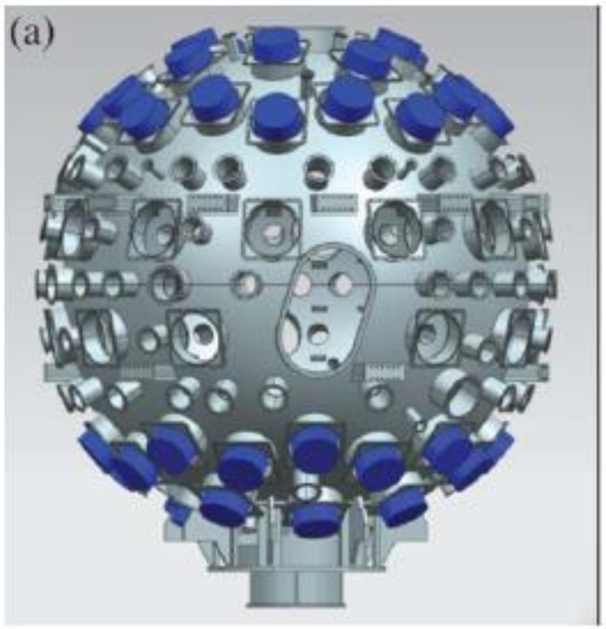
Hydrodynamic scaling does not include important physics such as laser-plasma interactions and the NIF polar geometry

V_{imp} =constant, Pressure=constant, α=constant

$E_{Laser} \sim R^3$ $Power_{Laser} \sim R^2$ Mass $\sim R^3$



NIF beam port configuration



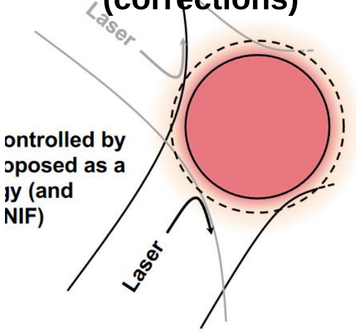
Degradation mechanisms affecting the fusion yield of OMEGA implosions have been quantified through statistical mapping to the experimental data

Yield degradation → $$\text{YOC=Yield-Over-Clean}=\frac{\text{Yield (measured)}}{\text{Yield (1D codes)}}$$

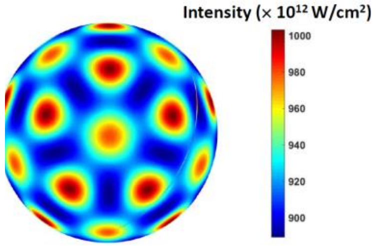
CBET/1D physics? **Beam mode** **Short wavelengths** *ℓ=1* **T-decay**

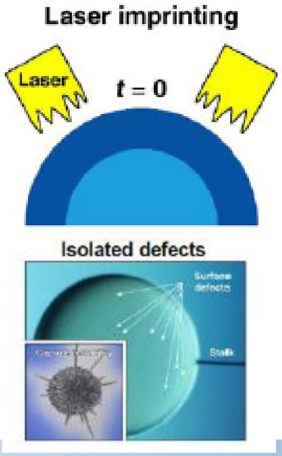
$$YOC\sim\left(\frac{Rb}{Rt}\right)^{b_1} e^{-(b_2+b_3\alpha+b_4CR)\sigma_{rms}^{b_5}}\left(\frac{\alpha_F^{b_6}}{IFAR}\right)^{b_7,b_8} Max\left[\left(\frac{T_{max}}{b_9T_{min}}\right),1\right]^{b_{10}} YOC_{He3}^{b_{11}}YOC_{res}$$

1D coupling (corrections)

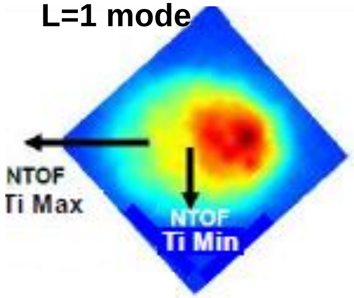


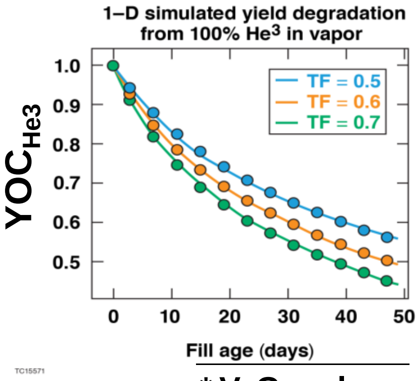
Beam mode





L=1 mode





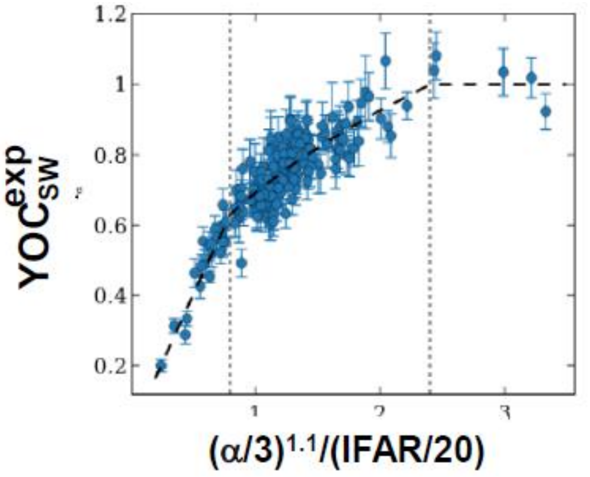
* V. Gopalaswamy, Nature 565, 581–586 (2019)
** A. Lees, Phys. Rev. Lett.127, 105001 (2021)

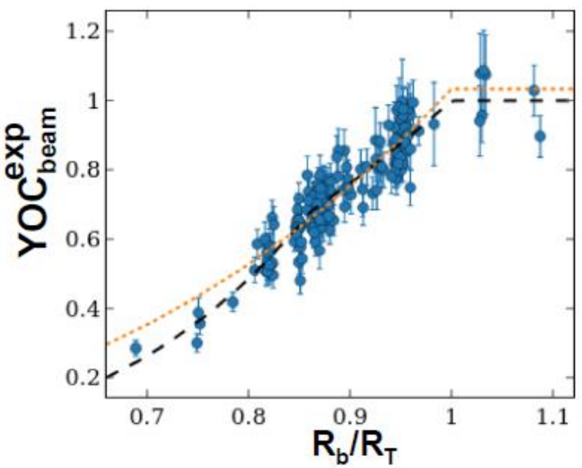
The result of the mapping provides individual dependencies[1] of each degradation mechanism and an accurate predictive tool

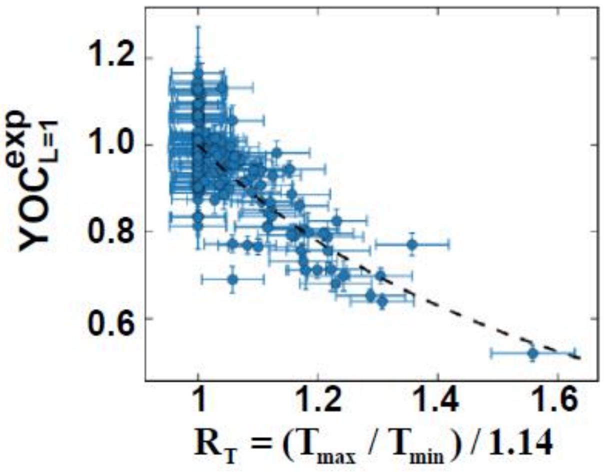
$$\mathrm{YOC}_{exp} = \text{Yield-Over-Clean} = \frac{\text{Yield (measured)}}{\text{Yield (1D codes)}}$$

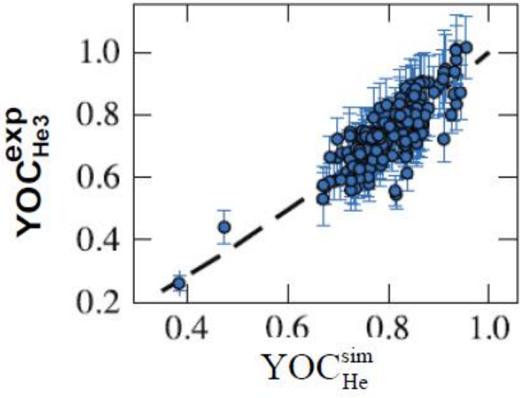
Short wavelength stability | **Beam mode + energetics** | **Beam mode** | **Mode 1** | **Fill Age**

$$\mathrm{YOC}_{exp} \sim \left(\frac{(\alpha/5)^{1.3}}{(IFAR/47)}\right)^{0.4-0.85} \left(\frac{\mathrm{R_b}/R_t}{0.86}\right)^{2.3-4.2} \frac{1}{CR^{0.7}} \left(\frac{\mathrm{T_{min}}}{\mathrm{T_{max}}}\right)^{1.4} \left(\mathrm{YOC}_{He3}^{LILAC}\right)^{1.2}$$









[1] A. Lees et al, PRL (2021), PoP (2023)

Predictive statistical models of the neutron yield are extremely accurate and speed up validation of new designs