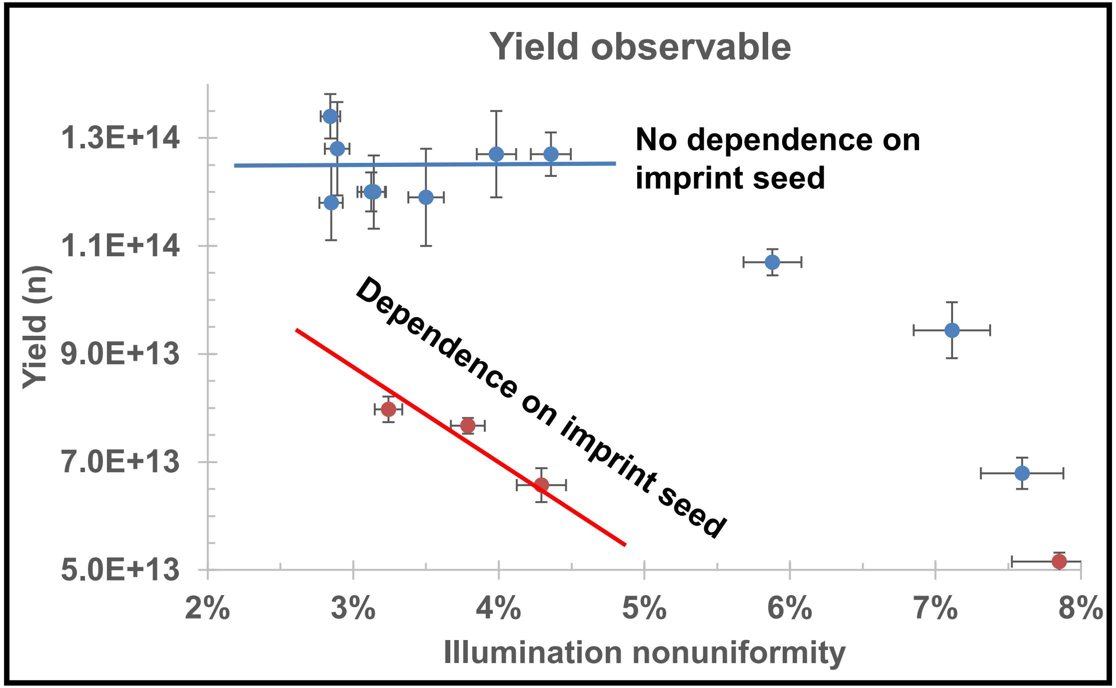
A Systematic Study of Laser Imprint for Direct Drive—From Seeds to Integrated Implosions



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64th Annual Meeting of the American Physical Society Division of Plasma Physics
Spokane, WA
17-21 October 2022

Summary

Imprint limits the performance of high-compression, OMEGA cryogenic implosions at low but not high adiabats

- The sensitivity of α (adiabat) = 4.5 and α = 3.5 designs to laser imprinting was assessed for high yield targets (> 10^{14}) using a series of implosions with varying Smoothing by Spectral Dispersion (SSD) bandwidth levels
- Planar foil experiments were carried out to measure single-beam imprint
- 2d, Draco hydrodynamic simulations show the same trends as the experimental data
- Low adiabat, $\alpha \leq 3.5$, implosions would benefit from higher SSD bandwidth to reduce imprint perturbation
- High adiabat, $\alpha \geq 4.5$, implosions are not dominated by imprint perturbation
- Current high-performance cryogenic implosions on OMEGA are not limited by imprint

Collaborators

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Outline

- Motivation for SSD Scan
  - Measure imprint effect
- Experimental Setup
  - Cryogenic implosions on OMEGA
- High mode seed measurement with 2d-VISAR
  - Measure single-beam perturbations for simulations in planar geometry
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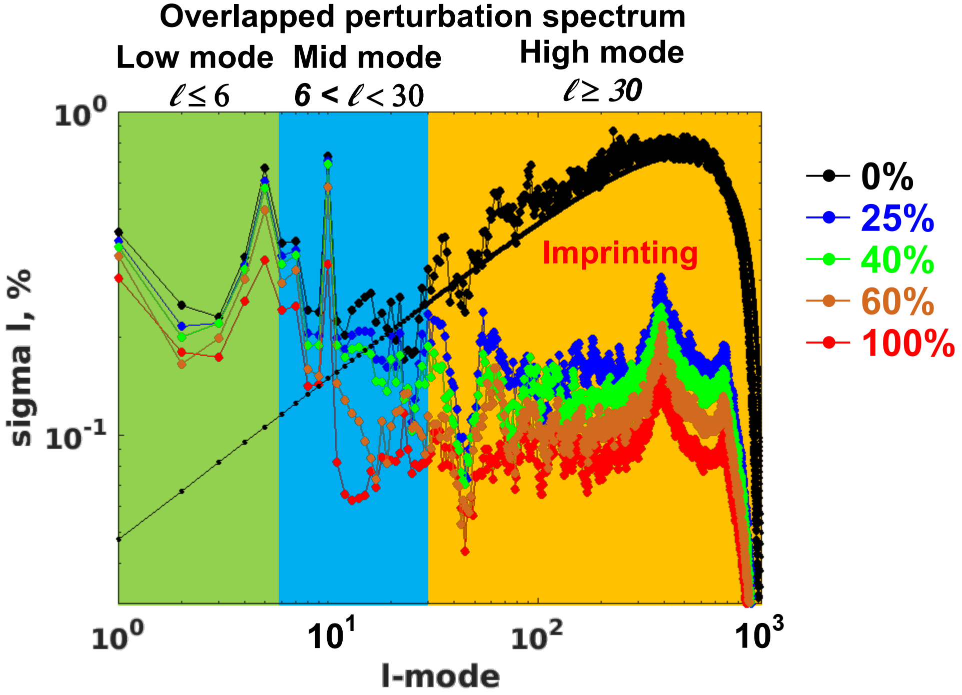
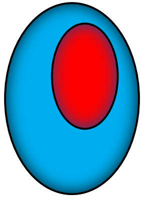
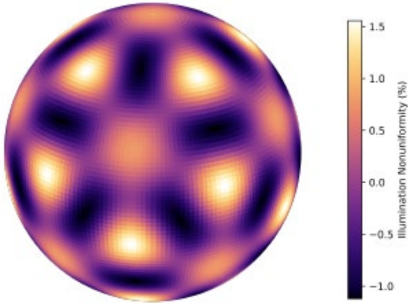
The goal of the SSD Scan experiment was to study the how laser imprint seeds high-mode perturbations



Low mode $l \leq 6$



Mid mode $6 < l < 30$



Varying the SSD bandwidth significantly changes the high-mode perturbation seeds

The parameter I_α is used to quantify the stability to short wavelength (SW) perturbations of OMEGA cryogenic implosions[1,2]

Nonlinear Rayleigh-Taylor (RT) bubble front penetration

$h_b = \beta(\alpha_F)gt^2 \sim \beta(\alpha_F)R$

$h_b/\Delta_{sh} \sim \beta(\alpha_F)\mathrm{IFAR}$

β related[3] to $1/\alpha_F$

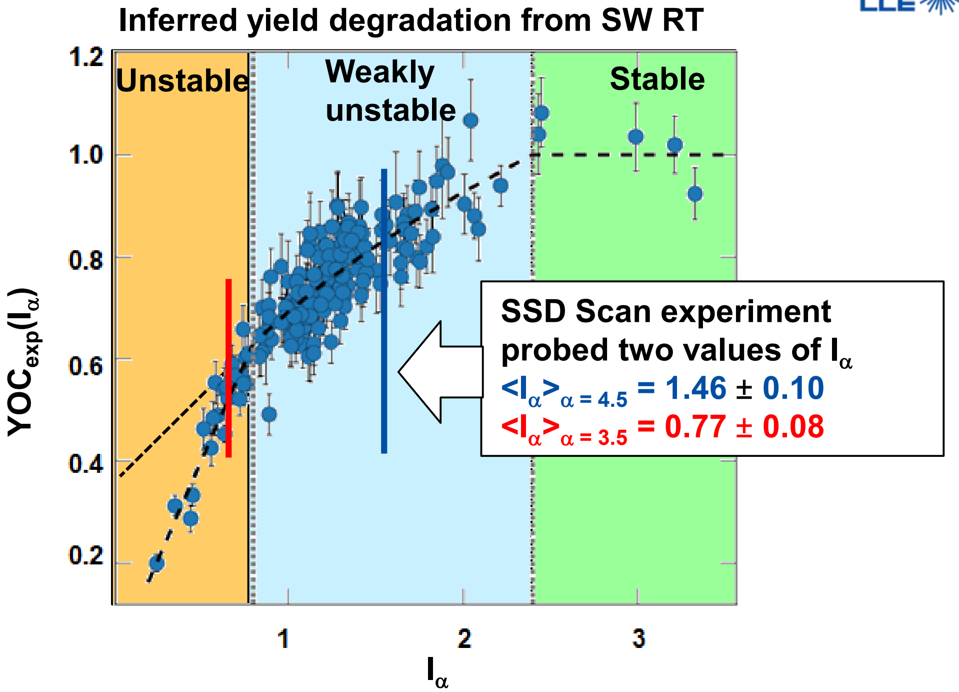
$$I_\alpha \equiv \frac{(\alpha_F/3)^{1.1}}{\mathrm{IFAR}/20}$$

← Stability parameter[3,1] for short wavelength RT

$\alpha_F \propto P/P_F$ - minimum shell adiabat

IFAR – Inflight aspect ratio

SSD Scan experiment probed two values of the stability parameter



The SSD Scan implosions with α = 3.5 are unstable

[1] Goncharov, V. N., et al. *Physics of Plasmas* 21.5 (2014): 056315

[2] Lees, A.et al. *Physics of Plasmas* submitted

[3] Zhang et al, PRL (2018)

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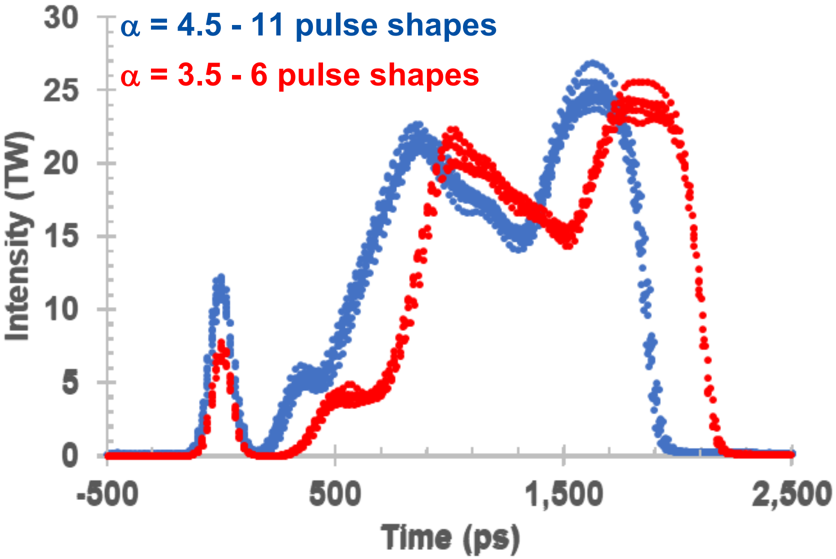
An SSD scan from 0 to maximum bandwidth has been completed for two adiabats, α = 4.5 and α = 3.5, to study the effect of high mode perturbations

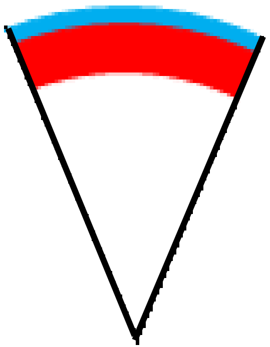


Pulse shapes were very reproducible

Total energy on target = 28.5 +/- 0.3 kJ

SSD[1-3]: 2d, 3 color cycle, 1/3 THz

X and y modulator bandwidths varied



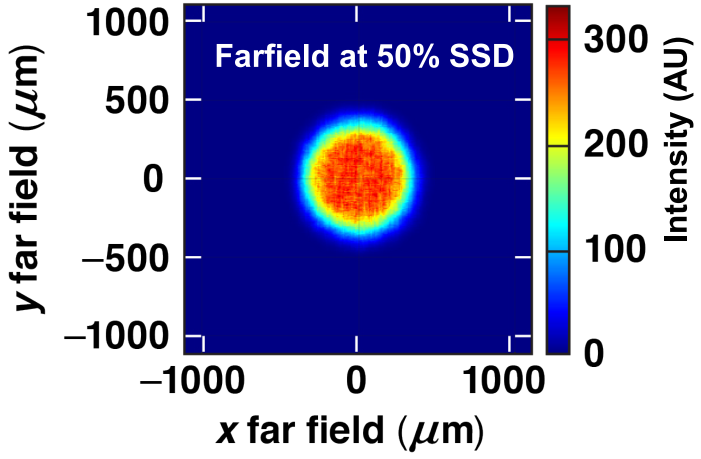
Cryogenic targets:

α = 4.5 and α = 3.5

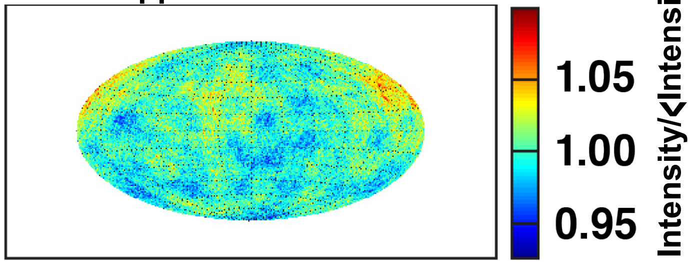
- 978 ± 3 μm OD
- 7.8 ± 0.1 μm CD shell
- 41.7 ± 0.6 μm DT ice layer

[1]S. Skupsky, et al., J. Appl. Phys. 66, 3456 (1989).
[2]S. P. Regan, et al., J. Opt. Soc. Am. B 17, 1483 (2000).
[3]S. P. Regan, et al., J. Opt. Soc. Am. B 22, 998 (2005).

A "hard sphere" model is used to calculate the overlap intensity from single-beam far fields calculated by convolving the DPP far field with the SSD kernel

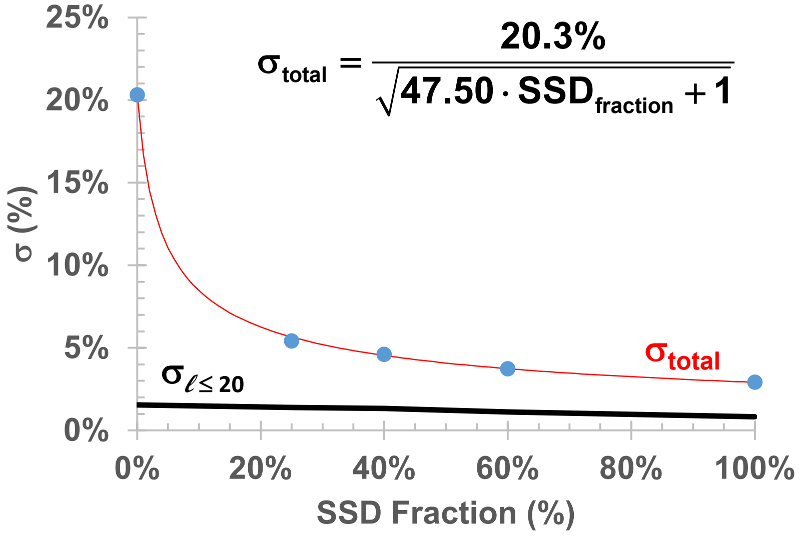


60 overlapped beams at 50% SSD



SSD fractional bandwidth converted to Illumination σ_{total} ($\sigma_{total}^2 = \Sigma\sigma_i^2$ $1 \leq \ell_i \leq 1000$)

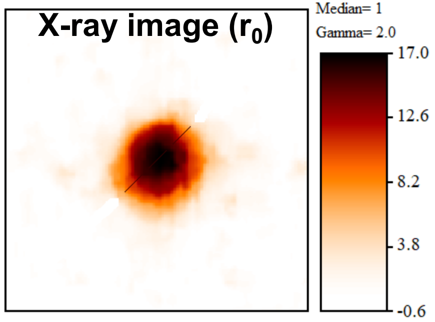
Analytic fit to calculated σ_{total}



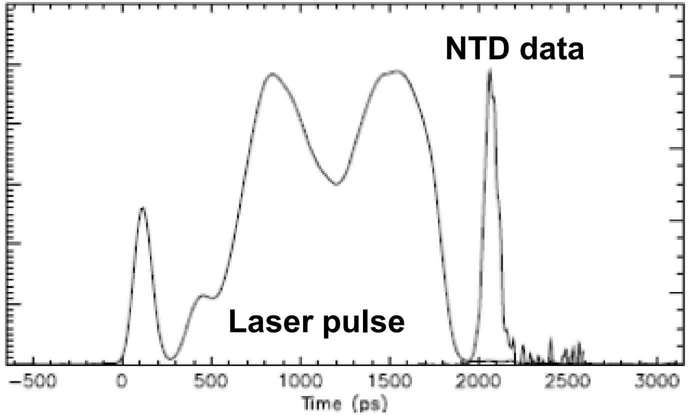
Data are obtained from six experimental measurements

Experimental Measurements:
- Neutron yield (Y)
- Total areal density (ρR)
- Ion temperature (kT_{ion})
- Radius at maximum compression (r_0)
- Time of peak neutron emission (Bang Time)
- Duration of neutron emission (Burn Width)

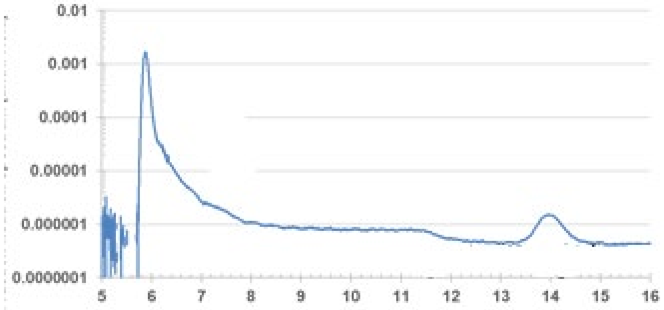
X-ray image (r_0)



NTD (Bang Time & Burn Width)

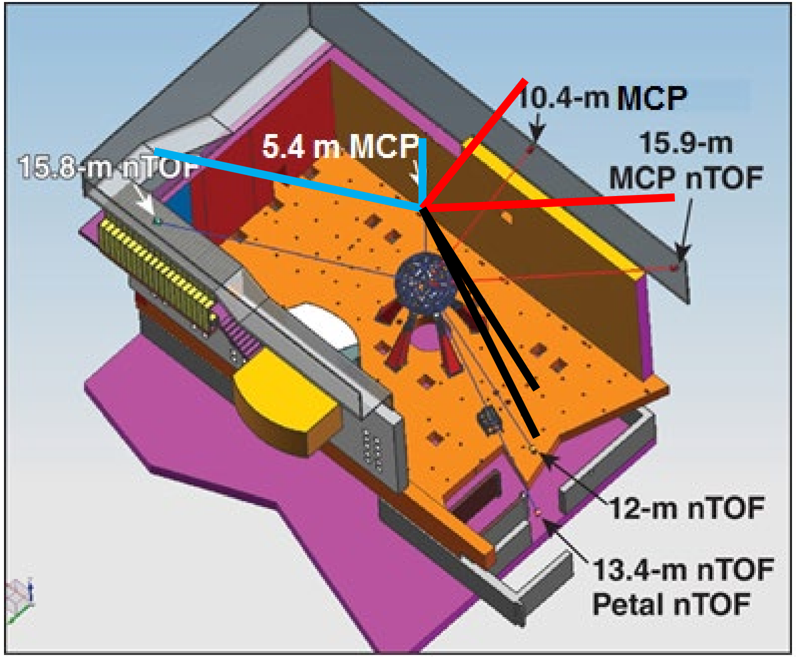


nToF Neutron spectrum (Y, ρR, & kT_{ion})

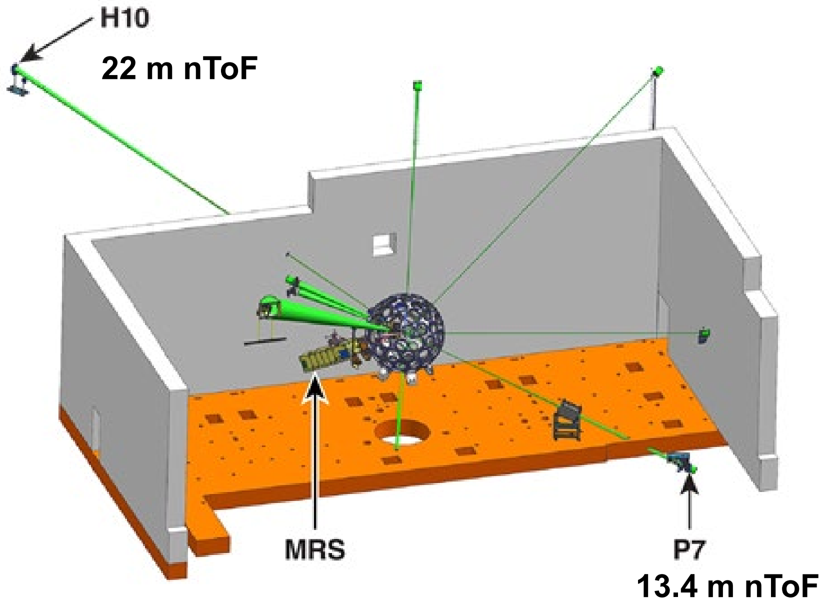


Yield, ion temperature, and areal density are measured along multiple lines-of-sight

6 nTOF lines-of-sight for yield and ion temperature measurements



3 lines-of-sight for ρr measurements



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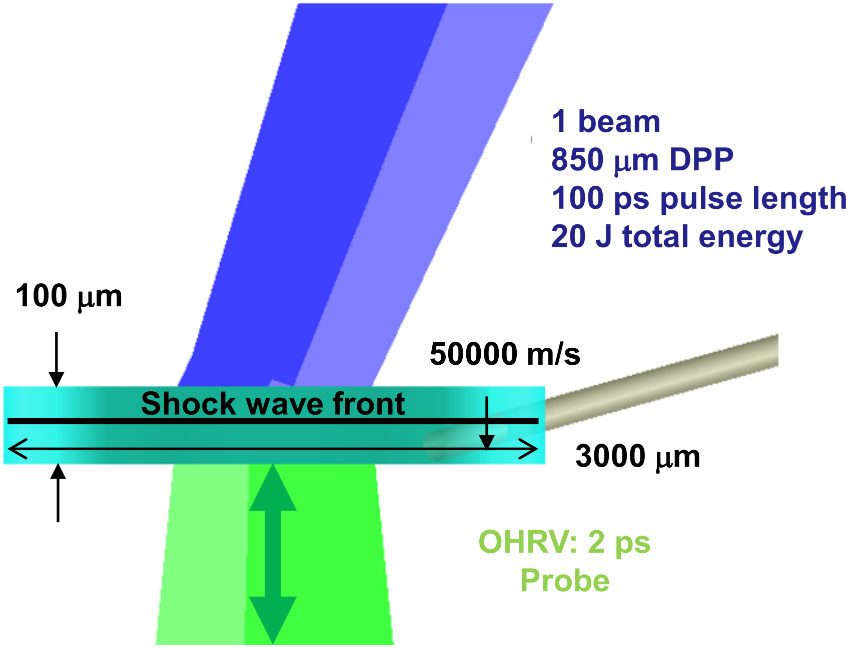
OHRV[1] (2d-VISAR) probes the shock front, related to imposed modulation on the ablation surface, providing a 2d map of the shock speed perturbation



Perturbation from single beam measured[2]

Planar geometry used
OHRV resolution = 3 μm
Integration time = 2 ps
Measurement taken ~1 ns after 100 ps picket

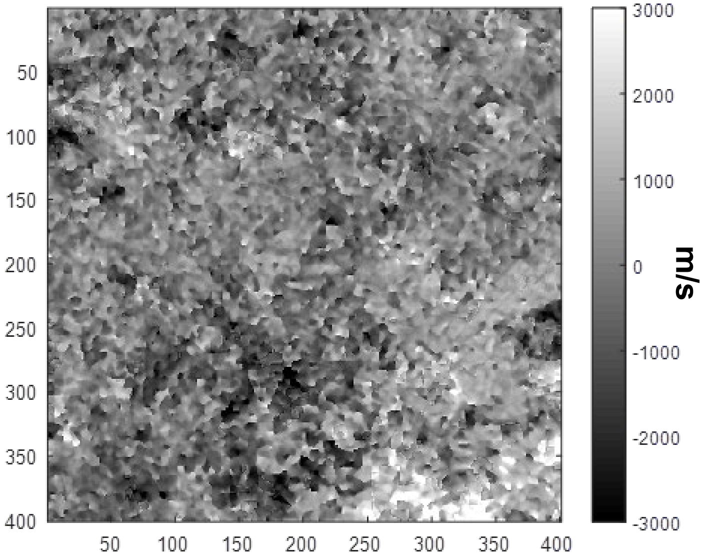
0 bandwidth and maximum bandwidth SSD measured

[1] P. M. Celliers, et al. Rev. Sci. Instrum. 81, 035101 (2010)
[2] J. L. Peebles et al. Phys Rev E 99(6)

The perturbation of shock wave speed was measured for 0 and maximum SSD bandwidth[1]

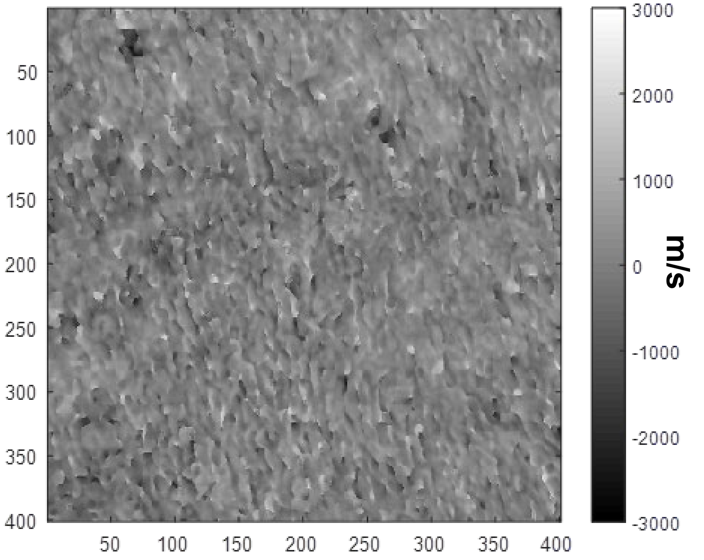
SSD: 0 bandwidth

σ_{RMS} = 1000 ± 90 m/s



SSD: maximum bandwidth

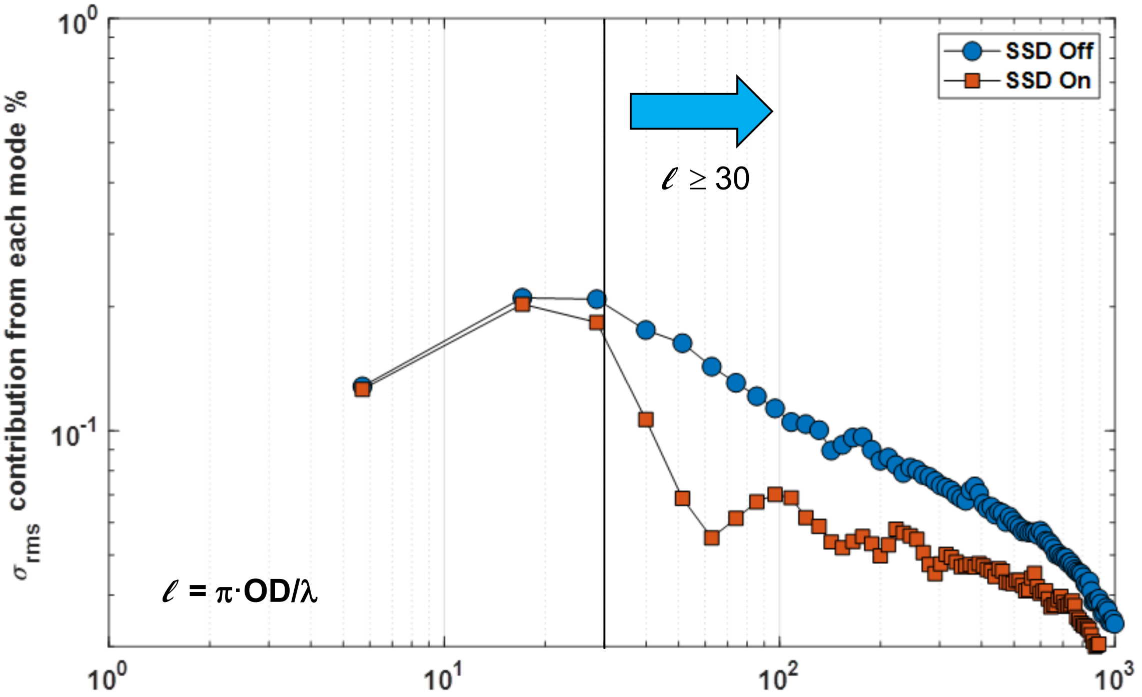
σ_{RMS} = 430 ± 50 m/s



[1]J. L. Peebles et al. Phys Rev E 99(6)

2d VISAR-speed σ_{RMS} shows that SSD at maximum bandwidth reduces the high-mode, $\ell \geq 30$, perturbations

2d-VISAR σ_{RMS} single beam spectrum for a 980 μm OD target



ℓ - mode

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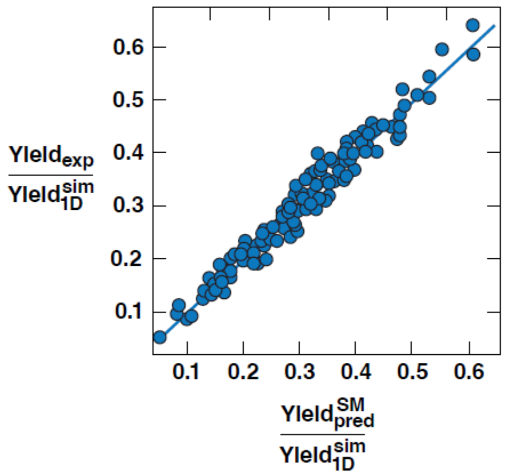
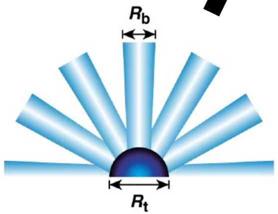
Statistical modeling (SM) of experimental data mapped onto simulated data is used to predict implosion performance and extract physical dependencies

$$YOC^{exp} \equiv \frac{Yield^{exp}}{Yield^{sim}_{1D}} \approx YOC_{beam}\left(\frac{R_b}{R_t}, CR\right) YOC_{sw}(\alpha, IFAR)\, YOC_{\ell=1}\left(\frac{T^{max}_{exp}}{T^{min}_{exp}}\right) YOC_{^3He}$$

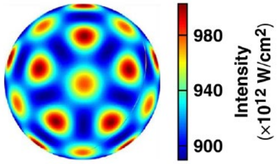
YOC measured vs YOC predicted



TC16266b

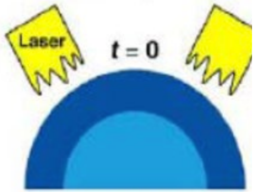


OMEGA illumination pattern*

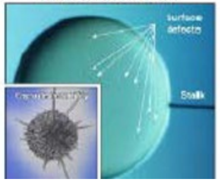


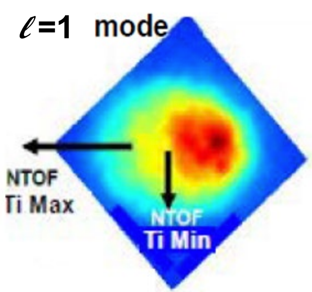
TC15655

Laser imprinting

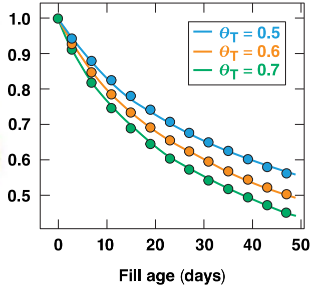


Isolated defects





1-D simulated yield degradation from 100% He^3 in vapor



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

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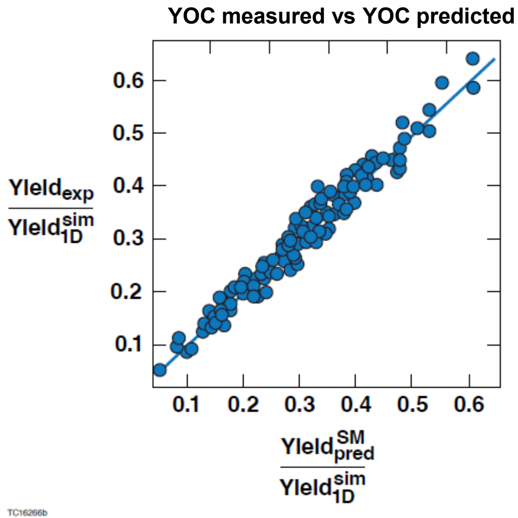

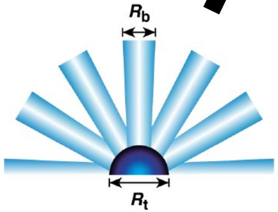

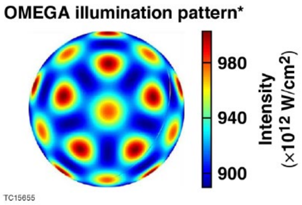

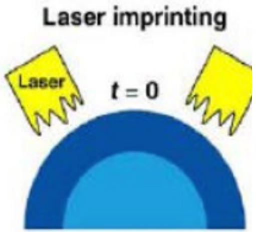

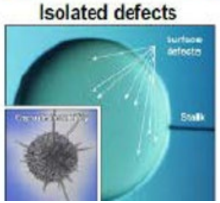

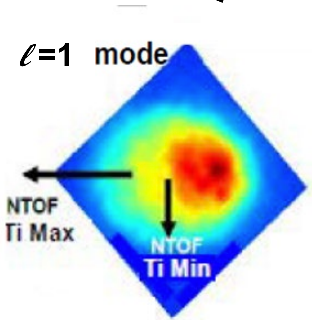

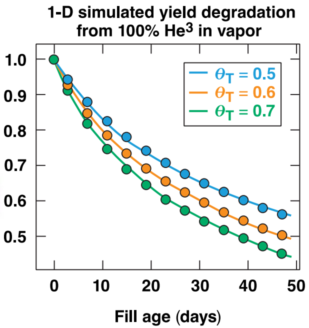

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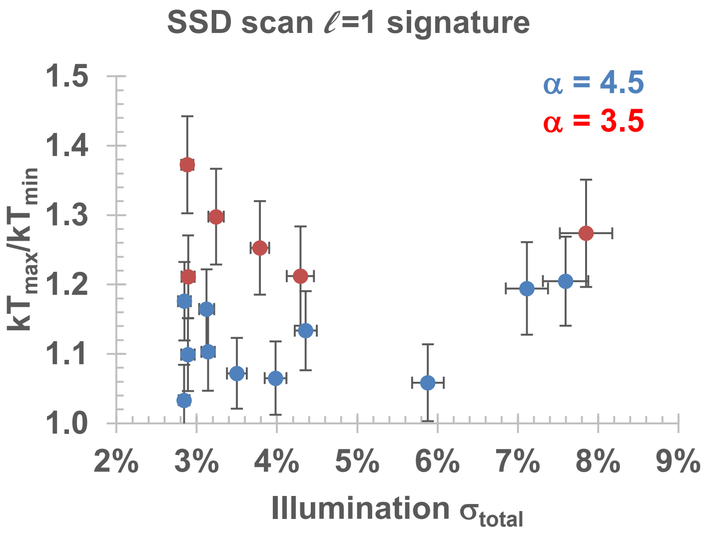
[2] A. Lees et al, Phys. Rev. Lett. 127, 105001 (2021)

Shot-to-shot variations due to the ℓ=1 mode are significant and their impact needs to be accounted for especially when comparing low adiabat implosions

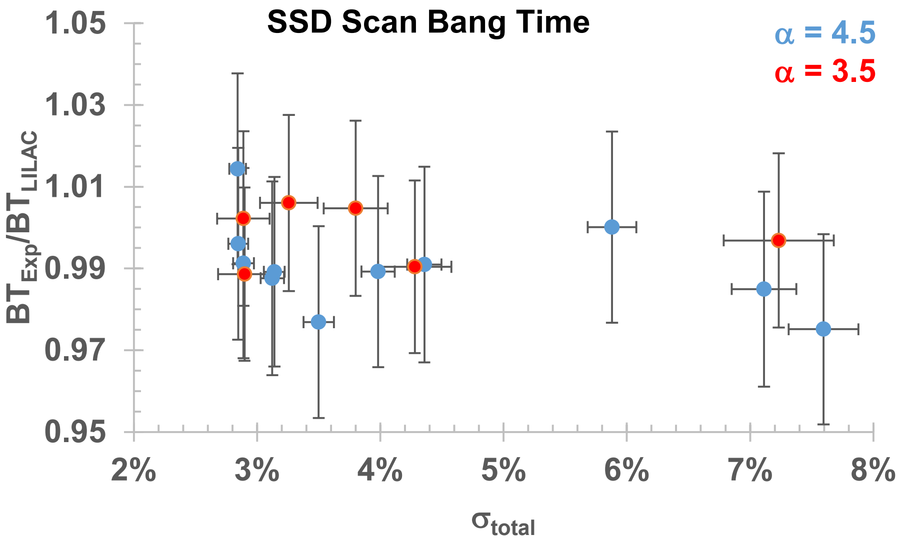
- **All shots from α = 3.5 scan also showed large Tion asymmetries ,kT_{max}/kT_{min}, > 1.25, (ℓ= 1 perturbation)**

- **Statistical Model predictions can account for ℓ=1 variations, slight changes in adiabats, convergence ratios, and in-flight aspect ratios**



The SM predictions are used to adjust for shot-to-shot variations when comparing implosion results as the SSD bandwidth is varied

LILAC, 1d-hydro simulations show good agreement of simulated versus measured time of peak neutron emission (Bang Times)



$\alpha = 4.5$, $\langle BT_{Exp}/BT_{LILAC} \rangle = 0.99 \pm 0.01$

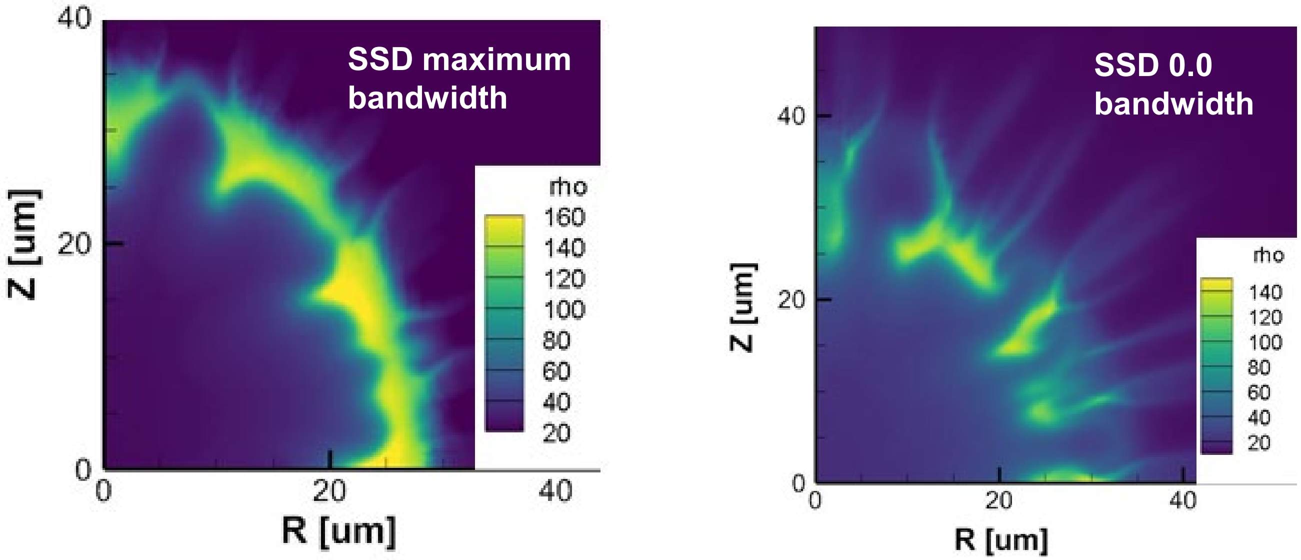
$\alpha = 3.5$, $\langle BT_{Exp}/BT_{LILAC} \rangle = 1.00 \pm 0.01$

BT = Bang Time

1d simulations correctly capture the energetics for these implosions

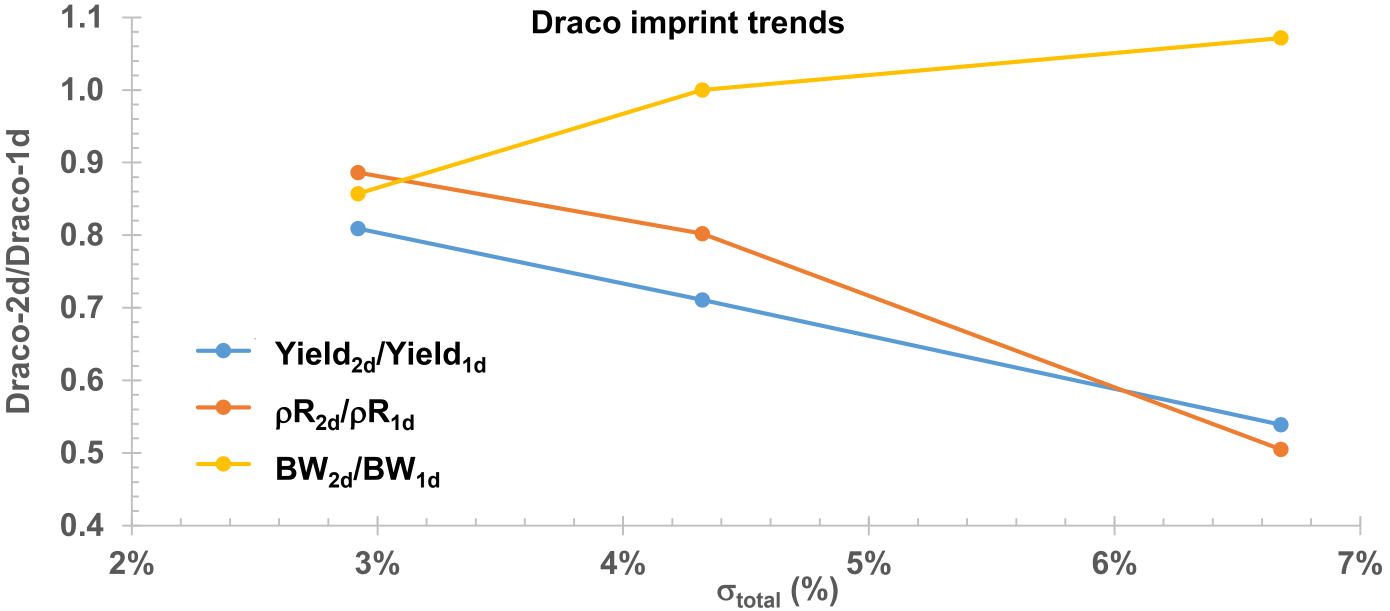
DRACO[1-5] simulations scanning SSD bandwidth use latest physics models and include perturbation modes up to $\ell = 124$

Bang-Time Profiles



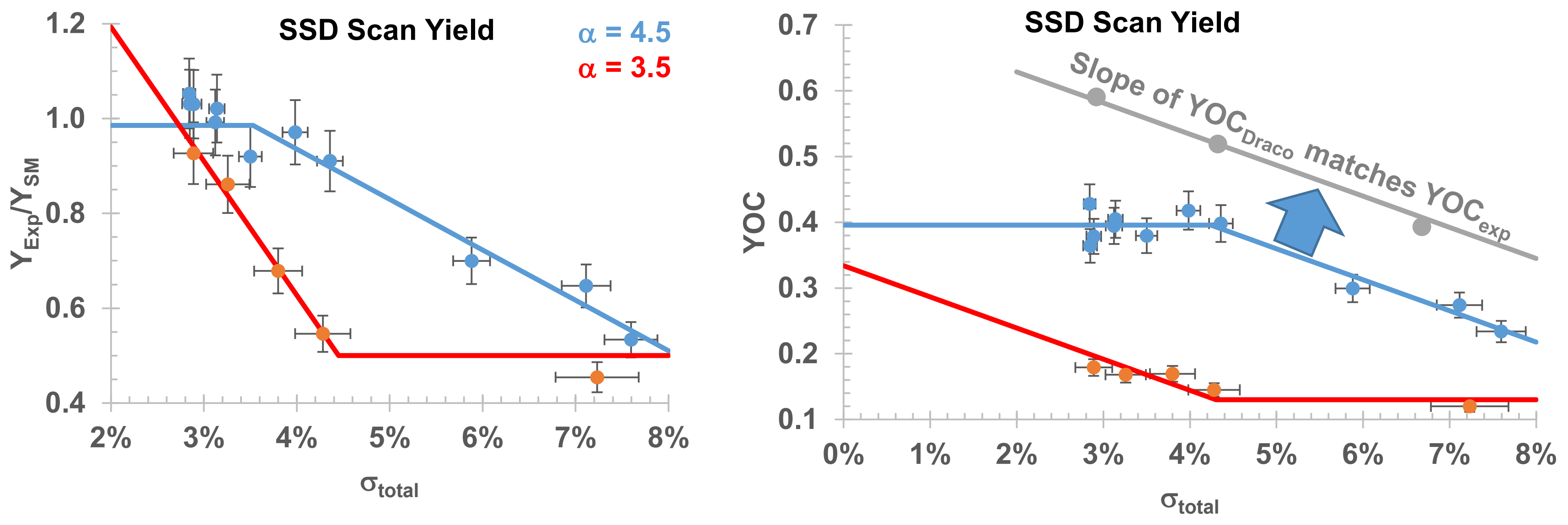
[1]P. B. Radha et al., Physics of Plasmas 12, 056307 (2005)
[2]J. Marozas e al, Phys. Rev. Lett. 120, 085001 (2018)
[3]D. Cao et al, Phys. Plasmas 22, 082308 (2015)
[4]J. Marozas, APS DPP 2009
[5]R. Epstein, Journal of Applied Physics 82, 2123 (1997)

DRACO simulations show a cold fuel shell that is highly perturbed and decompressed at peak compression when SSD is turned off



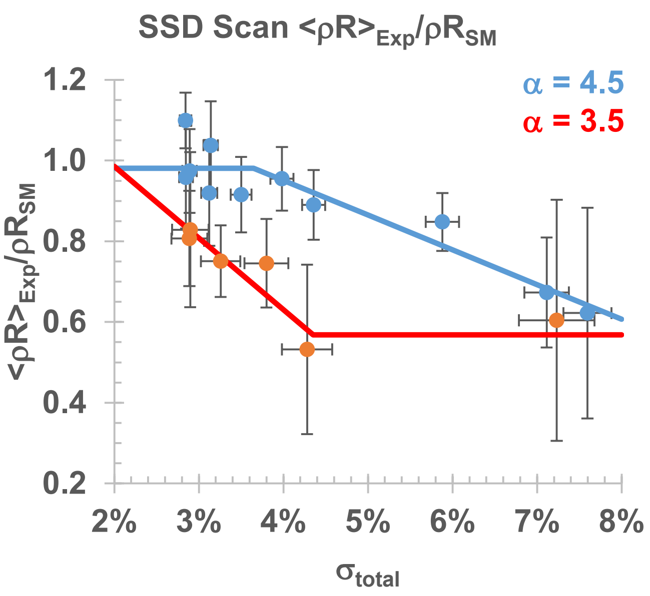
With SSD bandwidth set to 0
Yield is reduced, <ρR> is reduced, and Neutron emission lasts longer

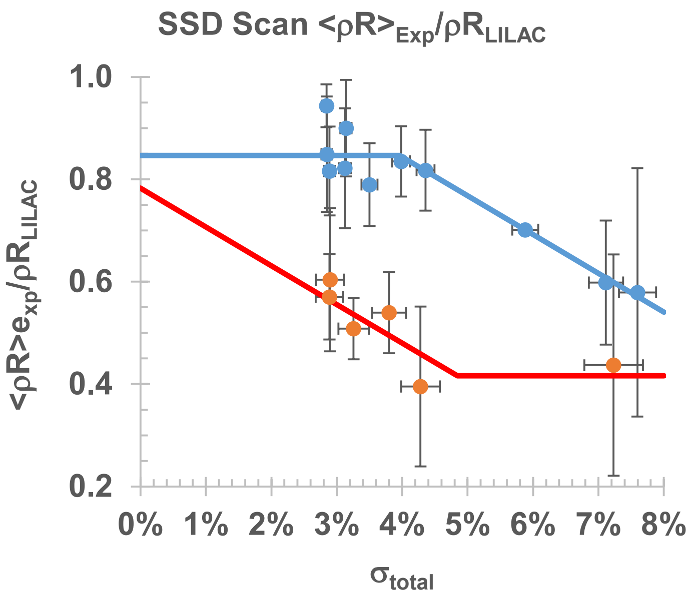
Neutron yield normalized to the statistical model shows different dependence on illumination σ_{total} for low and high adiabat implosions



Yield from low α implosions would benefit from higher bandwidth
Yield from high α implosions would not

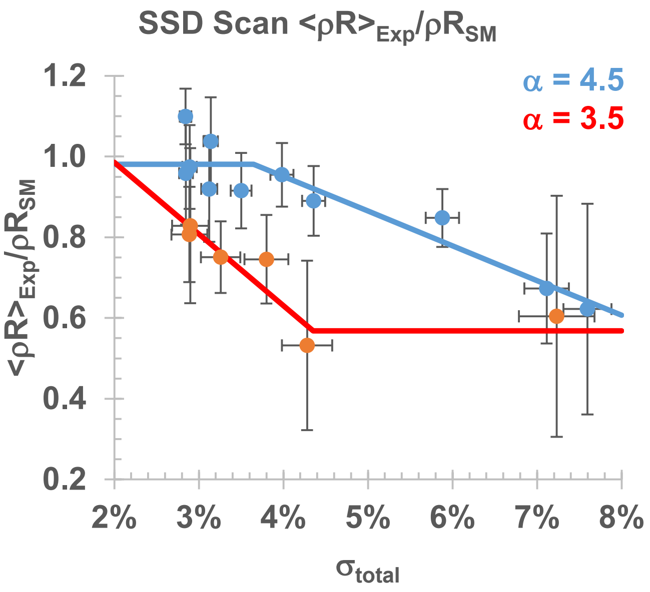
ρR shows a similar dependence on illumination σ_{total} as the yield

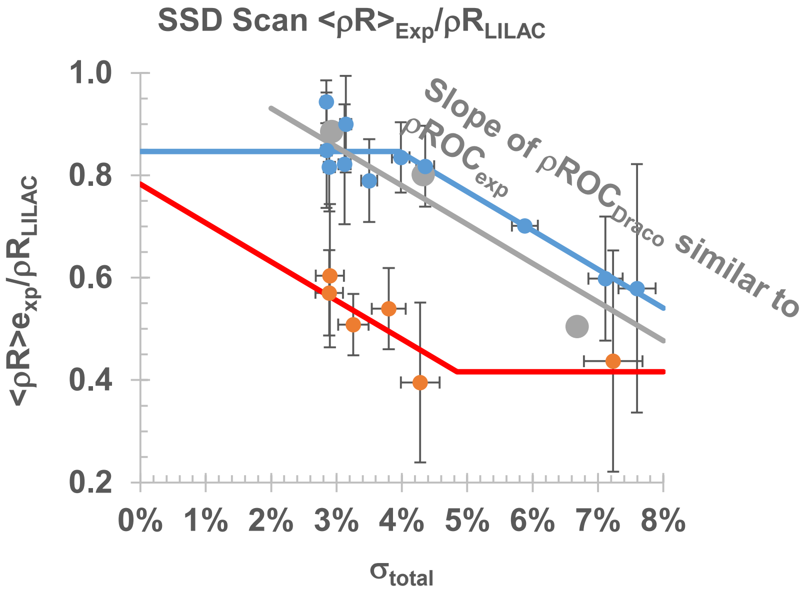




Areal density from low α implosions would benefit from higher bandwidth
Areal density from high α implosions would not

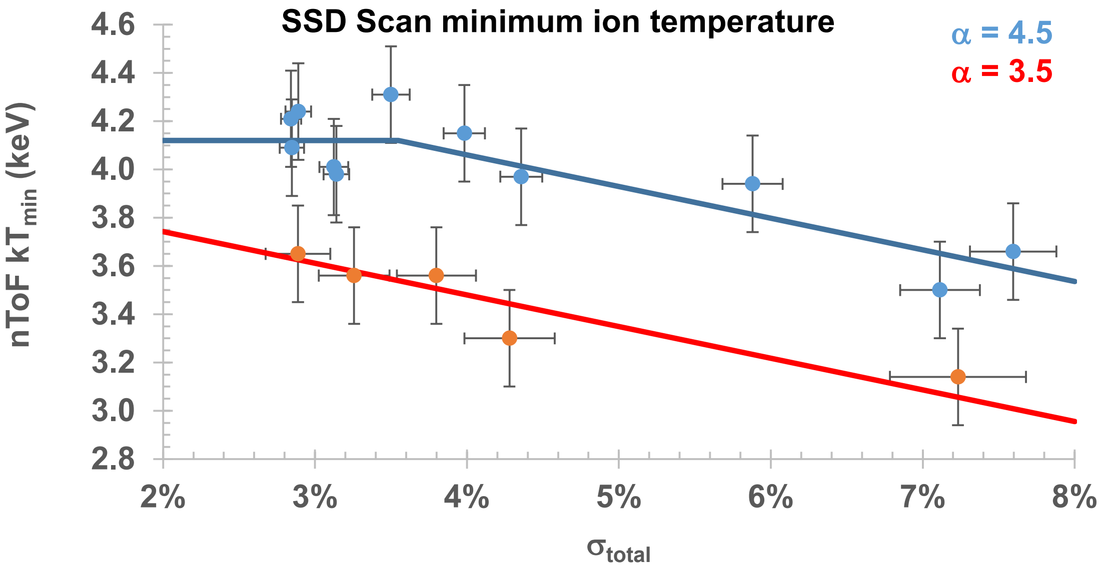
ρR shows a similar dependence on Illumination σ_{total} as the yield



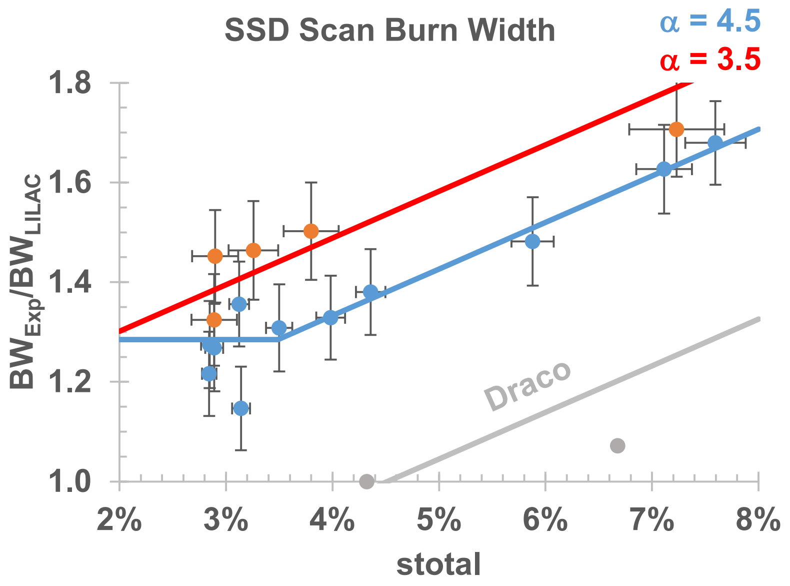


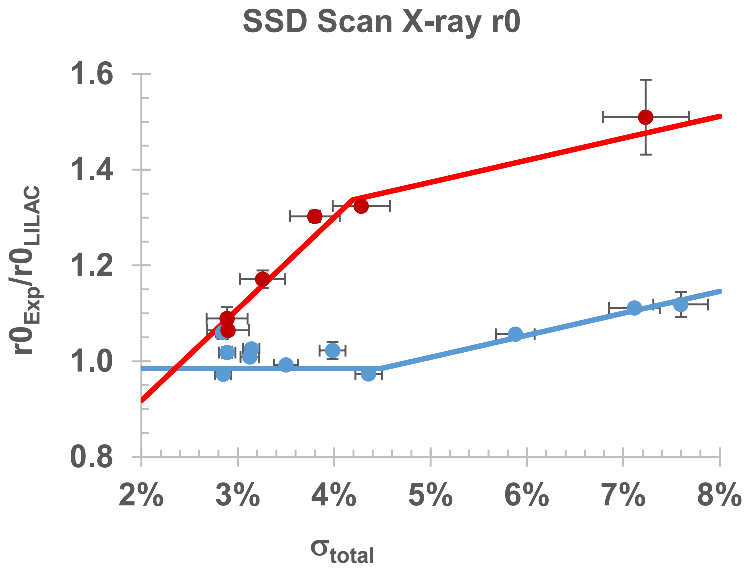
Areal density from low α implosions would benefit from higher bandwidth
Areal density from high α implosions would not

Measured minimum ion temperature shows a similar dependence versus Illumination σ_{total}



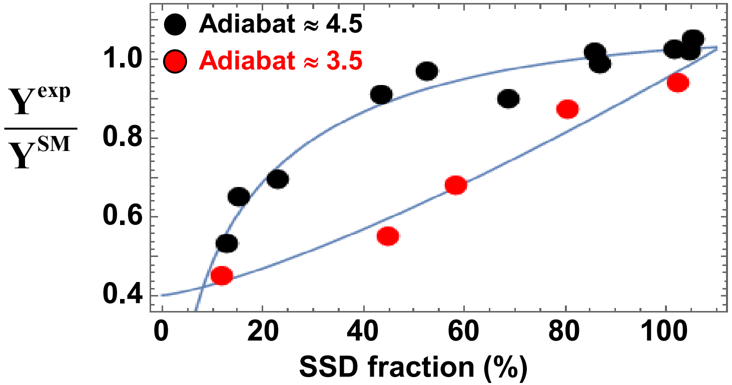
Burn width and size of the hot-spot, x-ray emission follow trends consistent with imprinting degrading low adiabats even at maximum SSD bandwidth

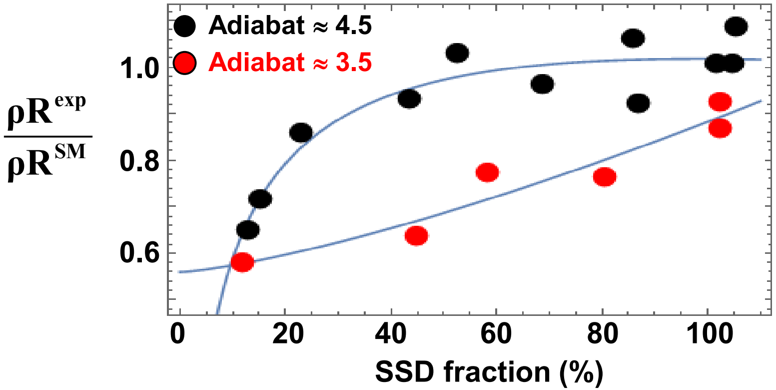


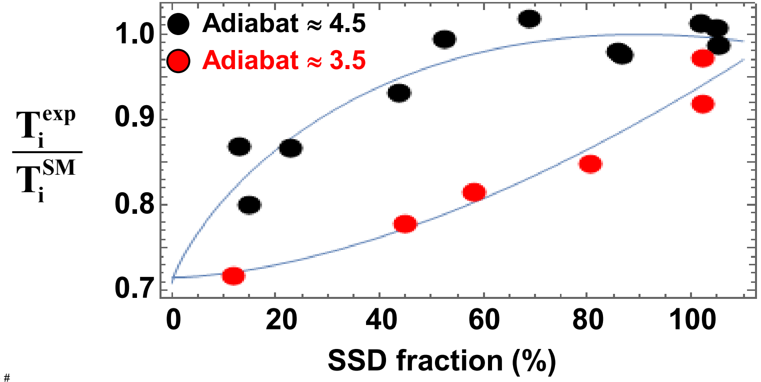


Draco shows a similar slope to experimental data when imprinting is degrading implosion

Neutron yield, areal density and ion temperature exhibit consistent behavior when plotted vs laser bandwidth (i.e. SSD fraction)







All ignition-relevant core properties (Yield, ρR, T_{ion}) would benefit from higher bandwidth at low adiabats (≤ 3.5) while high adiabat (≥4.5) is insensitive

Imprint limits the performance of high-compression, OMEGA cryogenic implosions at low but not high adiabats

- The sensitivity of α (adiabat) = 4.5 and α = 3.5 designs to laser imprinting was assessed for high yield targets (> 10^{14}) using a series of implosions with varying Smoothing by Spectral Dispersion (SSD) bandwidth levels
- Planar foil experiments were carried out to measure single-beam imprint
- 2d, Draco hydrodynamic simulations show the same trends as the experimental data
- Low adiabat, $\alpha \leq 3.5$, implosions would benefit from higher SSD bandwidth to reduce imprint perturbation
- High adiabat, $\alpha \geq 4.5$, implosions are not dominated by imprint perturbation
- Current high-performance cryogenic implosions on OMEGA are not limited by imprint

Abstract

A study of laser imprint for laser direct drive (LDD) is presented through measurements of laser-imprint seeds, the associated hydrodynamic instability growth rates, the shell thickness, and a systematic integrated study of the performance of imploded cryogenic DT ice and gas-filled shell targets under varying imprint seed levels and for two adiabat conditions. An understanding of how those implosions are degraded with the seed level is of paramount importance for inertial confinement fusion research. The seeds for imprint come from perturbations on the target [debris, surface imperfections, and engineering features] and from the speckle pattern in the laser beams and are amplified by the Richtmyer–Meshkov and Rayleigh–Taylor instabilities. Target seeds are minimized by careful selection and the imprint seed is changed by varying the bandwidth on smoothing by spectral dispersion (SSD). The seeds were characterized using a 2-D VISAR diagnostic and compared to results from radiation-hydrodynamic simulations. Growth-rate measurements and effects of the instabilities on the in-flight shell thickness and shell trajectory are discussed. The integrated experiment uses the stagnation measurements (neutron yield, areal density, x-ray images of hot-spot formation, fusion burn history) as metrics to gauge the implosion performance versus SSD bandwidth. The SSD bandwidth is quantified using a model that relates it to the □rms of the laser illumination. The emerging understanding of laser imprint from the OMEGA experiments will be discussed along with mitigation strategies and the implications for LDD ignition-scale targets for the National Ignition Facility. This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856.

ρROC ($\rho R_{exp}/\rho R_{LILAC}$) is correlated with the Burn Width ratio ($\text{Burn Width}_{exp}/\text{Burn Width}_{LILAC}$)