Recent Progress in Direct-Drive ICF

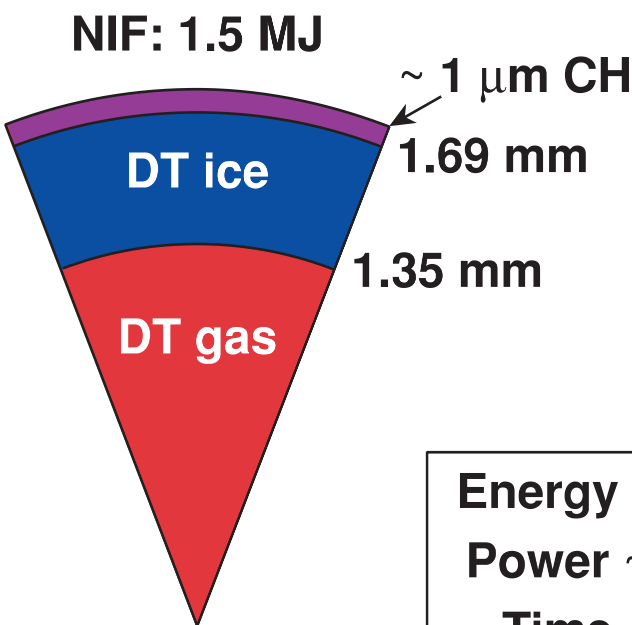
- **Near-1D performance has been measured for high-adiabat (α ~ 25) cryogenic D_2 implosions.**
- **Performance for low-adiabat (α ~4) cryogenic D_2 implosions is very close to 2-D *DRACO* predictions.**
- **Layering and characterization of cryogenic D_2 capsules are now routine; layer quality can be preserved well below the triple point.**
- **Adiabat shaping significantly improves target performance in warm, cryo surrogate CH capsule implosions.**
- **Deuterium re-shock experiments on OMEGA exhibit compressibility that agrees with the Saumon-Chabrier model.**
- **Fuel assembly experiments with fast-ignition targets are underway on OMEGA.**
- **Work is underway to reduce the laser illumination nonuniformitities to $\lesssim$ 1% rms.**

T. C. Sangster
University of Rochester
Laboratory for Laser Energetics

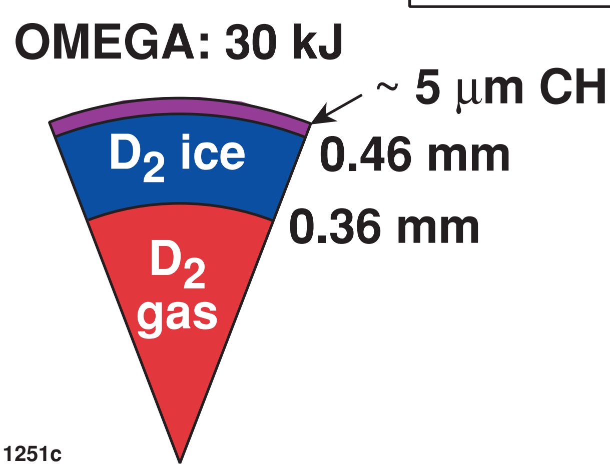
High Average Power
Laser Program Workshop
Naval Research Laboratory
5 – 6 December 2002

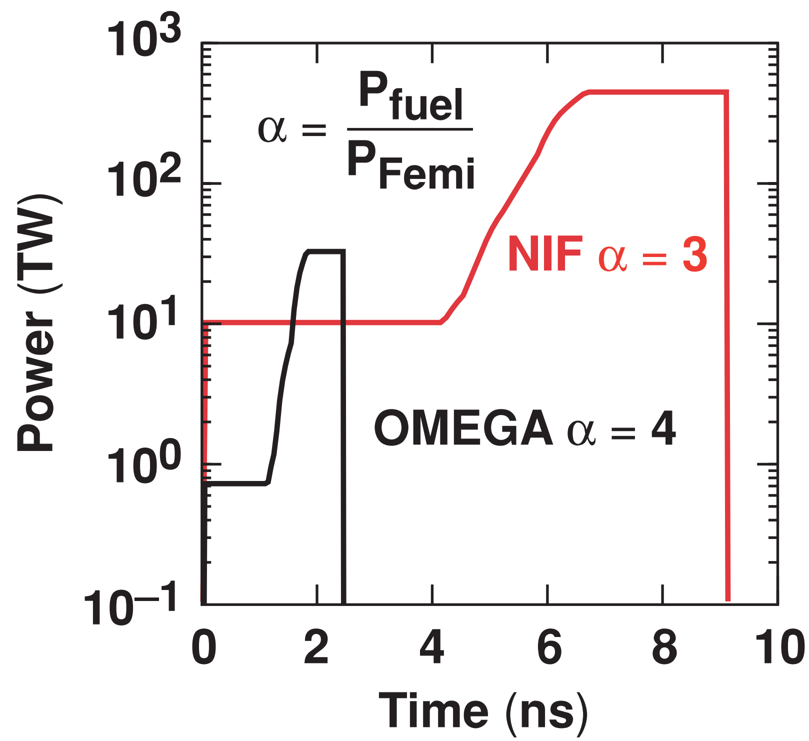
Ignition-Scaled Cryogenic Implosions

OMEGA cryogenic targets are energy scaled from the NIF direct-drive point design



Energy ~ radius^3;
Power ~ radius^2;
Time ~ radius





This "standard" capsule was developed
- to improve production reliability and
- to increase absorption.

Thicker-shell ignition designs with α shaping show baseline ignition performance.

E11251c

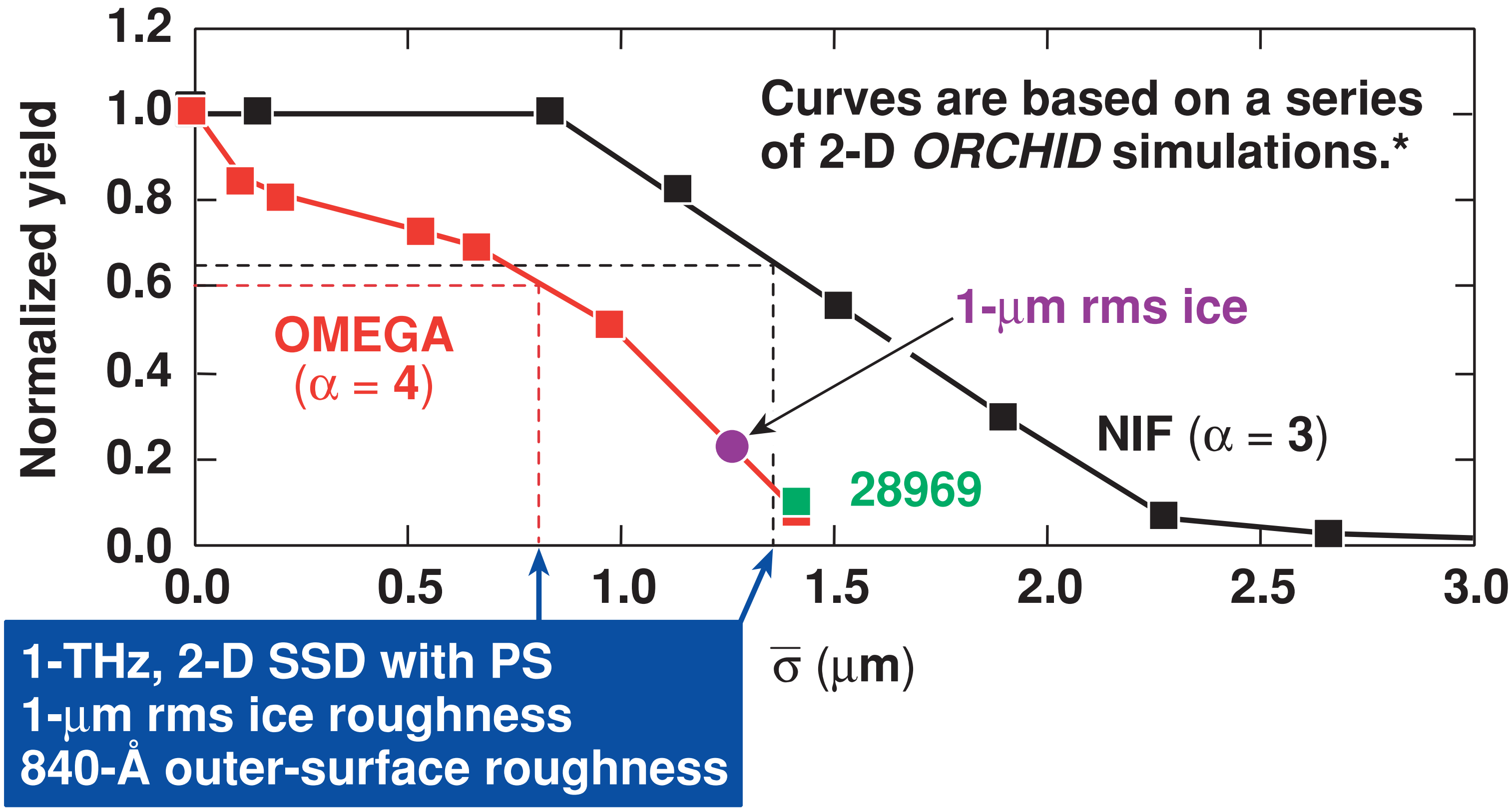
A stability analysis* of the $\alpha = 4$ design defines the ignition-scaling performance window for cryogenic implosions

UR LLE

- The NIF gain* and OMEGA yield can be related by

$$\bar{\sigma}^2 = 0.06\, \sigma^2_{\ell<10} + \sigma^2_{\ell\geq10},$$

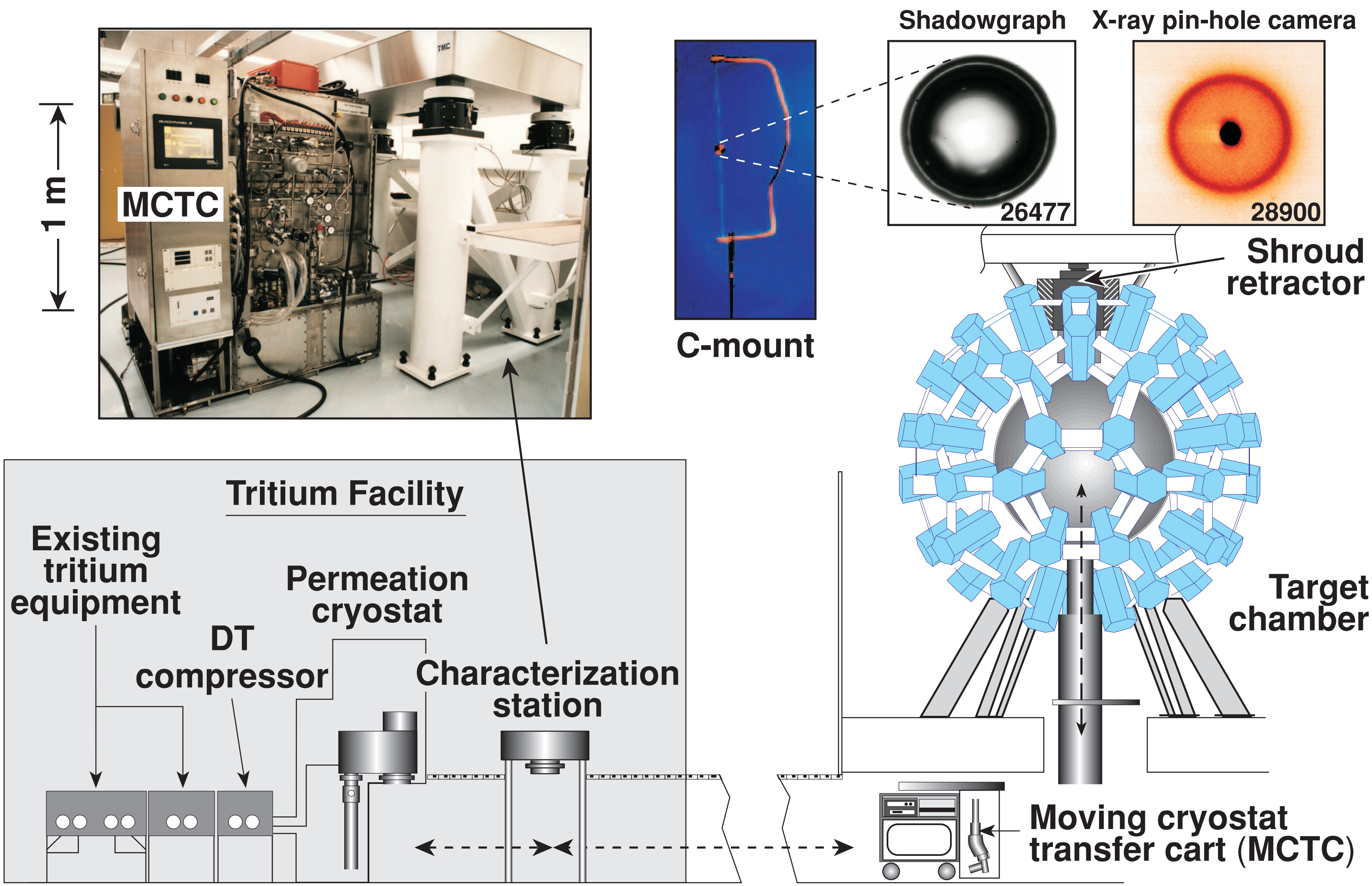
where the σ_ℓ's are the rms amplitudes at the end of the acceleration phase.



E12008b

* P. McKenty *et al.*, Phys. Plasma 8, 2315 (2001).

The life cycle of a cryogenic target is an engineering tour de force

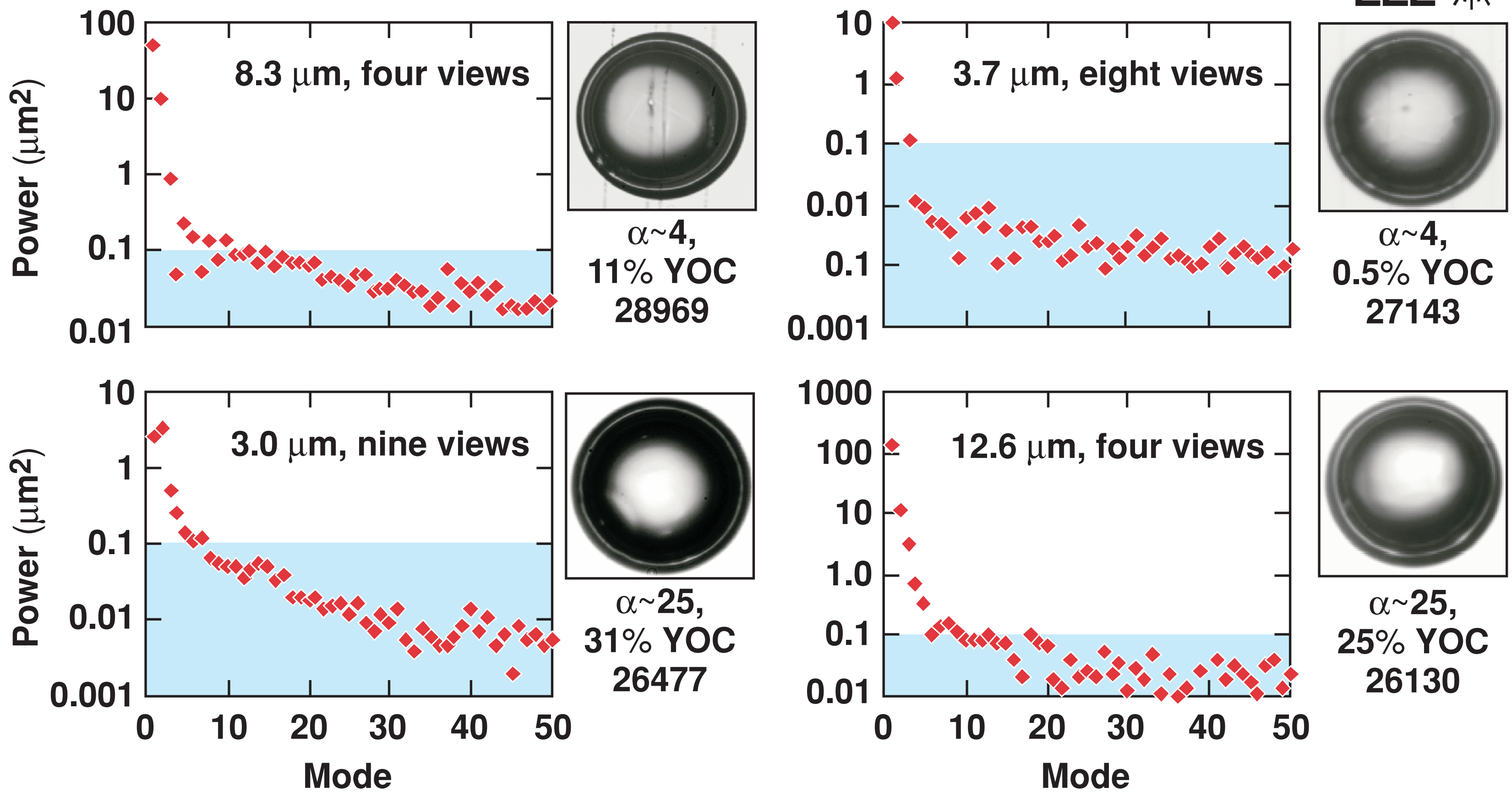


E12062

Ignition-Scaled Cryogenic Implosions

The Cryogenic Target Fabrication Group routinely delivers well-layered and fully characterized capsules

UR LLE



Cryogenic implosions to date (July 01 to October 02):

- **1-ns square (16 shots)**
- **α~4 (9 shots)**
- **α~4 with picket (December/January)**

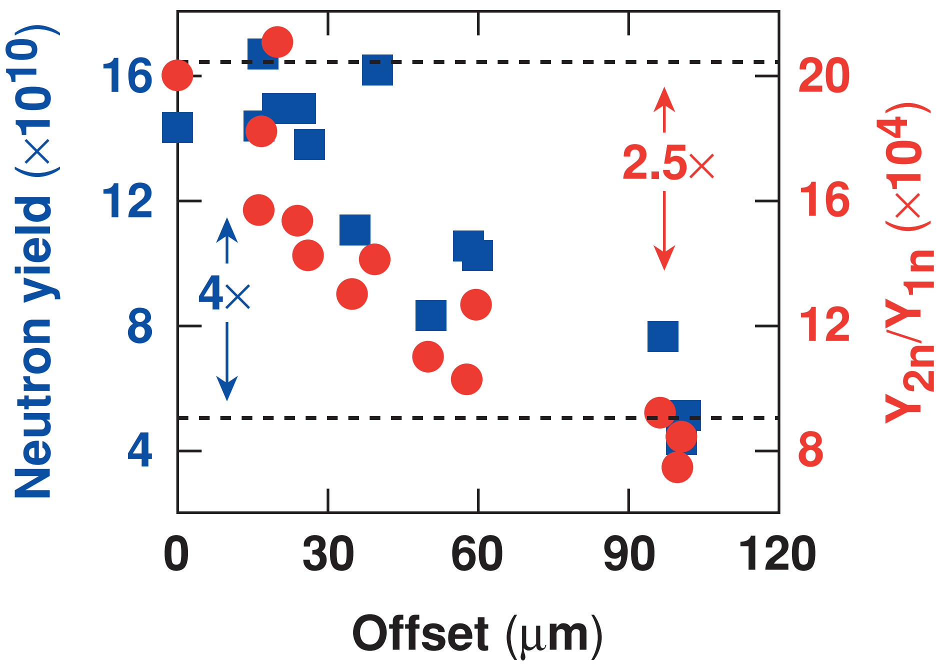
26

E12010b

Deliberate TCC offsets have a significant impact on implosion performance using D_2-filled CH capsules

UR LLE

Neutron yields from D_2-filled, 20-μm-CH capsules offset along the H7–H14 axis



For cryogenic implosions

Average offset prior to these experiments: 81 μm

"Smoking gun": sapphire windows (6) providing a view of the capsule

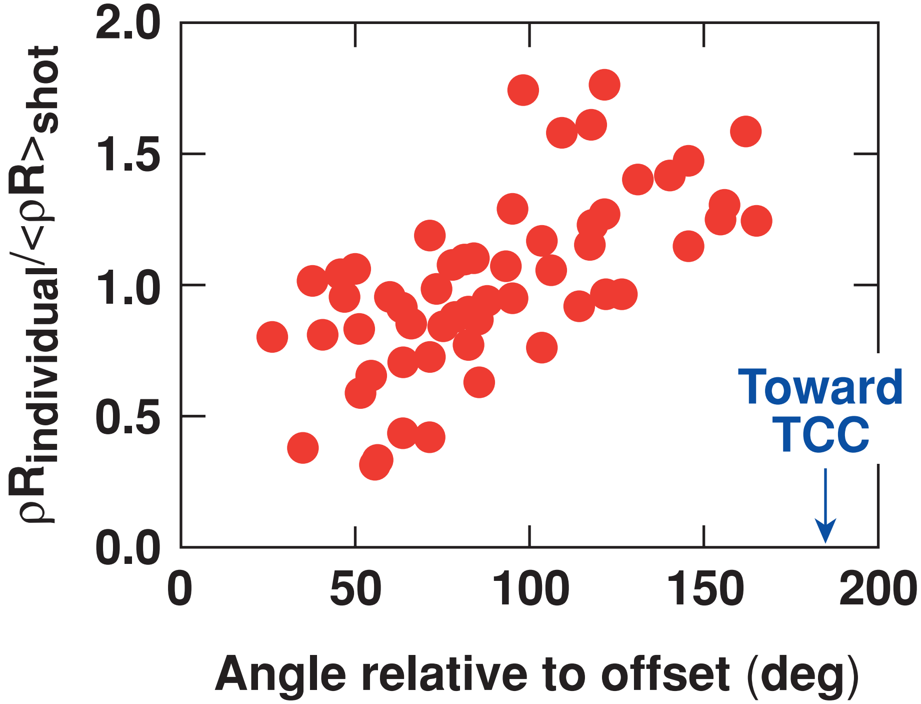
Average offset after re-engineering and cold calibration: 19 μm

Warm surrogate implosions showed that a systematic offset from TCC would likely explain the cryogenic implosion performance.

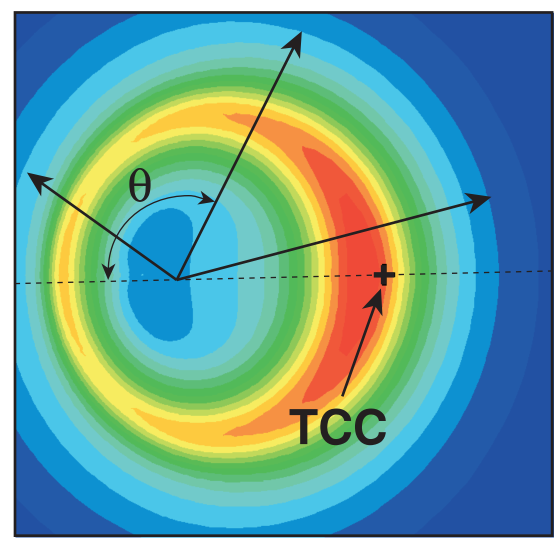
Individual cryo ρR measurements show the expected correlation with angle relative to the capsule offset

UR LLE

Fuel ρR is systematically higher on the side of the capsule toward TCC.



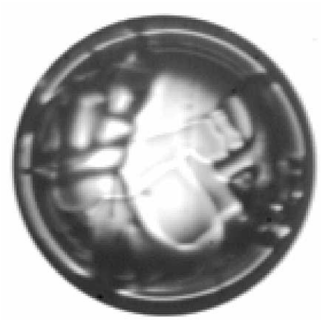
Density contours at peak burn from 2-D *DRACO* for a capsule offset by 50 μm with 1-μm-rms ice



This "geometric" analysis gives us confidence that we can accurately measure the capsule offset and understand the resulting performance.

E12014a

A comparison of shots 28900 and 26477 clearly shows the result of accurate TCC alignment (with $\alpha \sim 25$)



Drive pulse: 1 ns ($\alpha \sim 25$)

Shot 28900

Experimental		Clean 1-D (%)
Yield (1n):	1.27×10^{11}	96
Yield (2n):	1.17×10^{9}	84
Yield (2p):	2.03×10^{8}	112
$\langle \rho R \rangle$:	61 mg/cm^2	133
T_{ion}:	3.6 keV	157
Y_{2n}/Y_{1n}:	0.0092	85
Y_{2p}/Y_{1n}:	0.0016	114
TCC offset:	14±7 μm	

Shot 26477

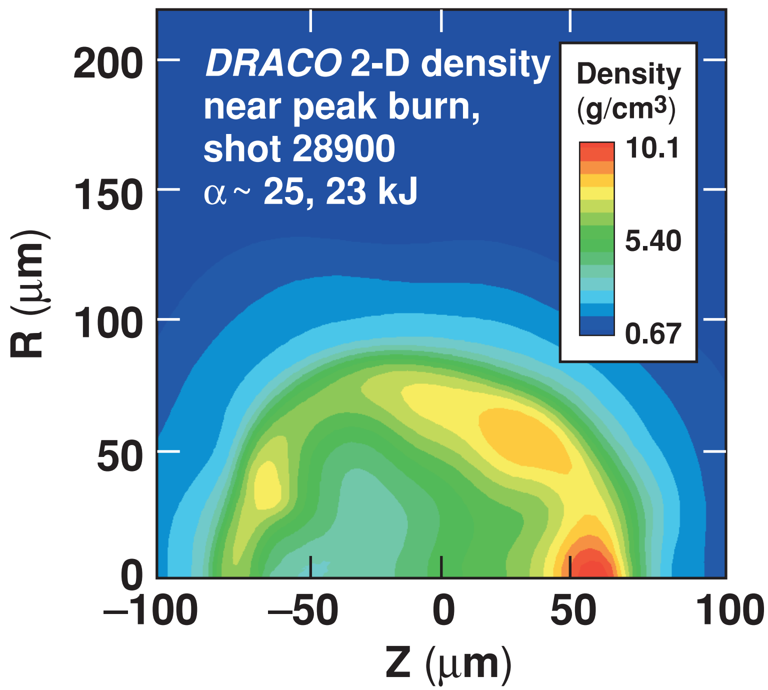
Experimental	Clean 1-D (%)
3.17×10^{10}	31
3.05×10^{8}	32
2.67×10^{7}	21
30 mg/cm^2	80
2.6 keV	117
0.0096	102
0.00084	66
85 μm	

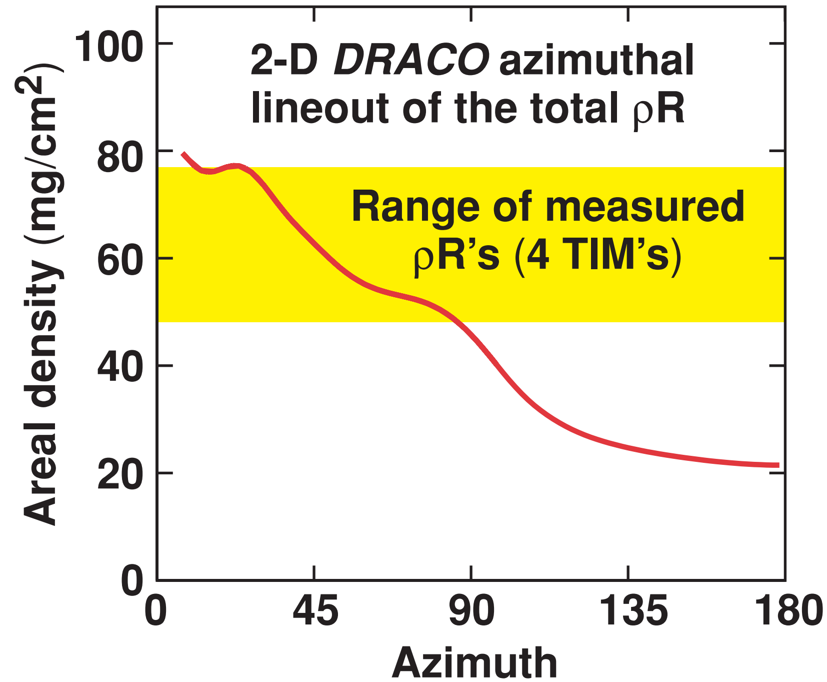
E12016a

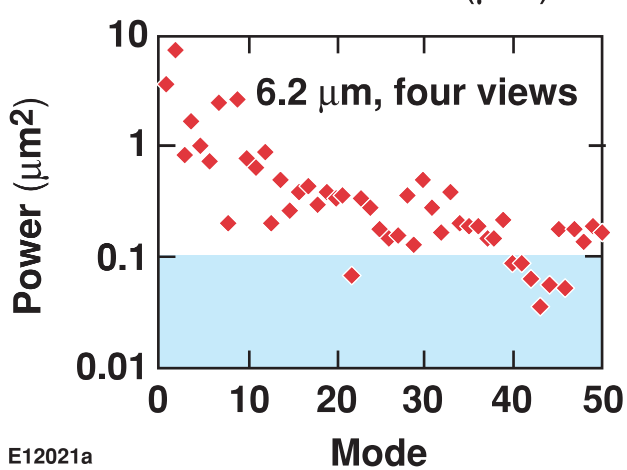
Ignition-Scaled Cryogenic Implosions

2-D *DRACO* accurately predicts the cold fuel areal density in shot 28900 ($\alpha \sim 25$)

UR LLE







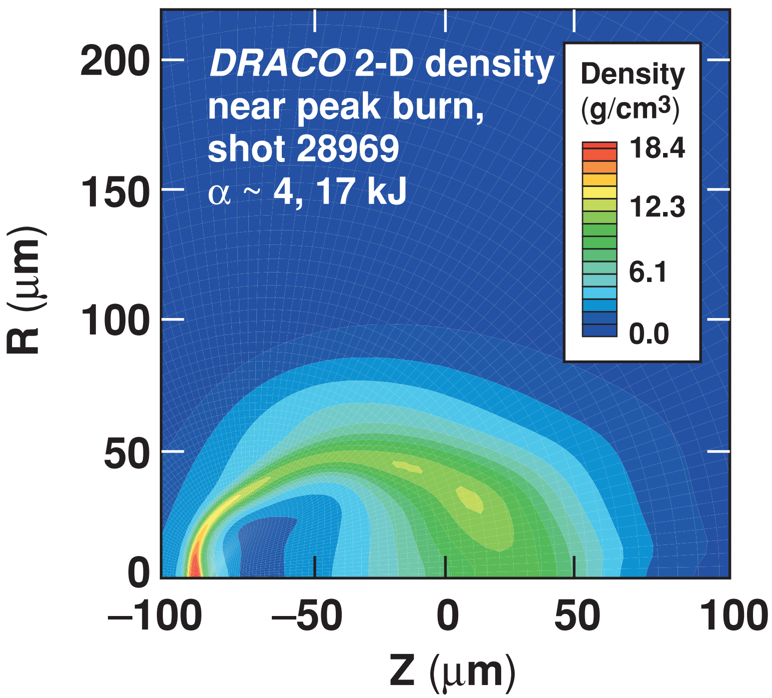
1 ns,
96% YOC
28969

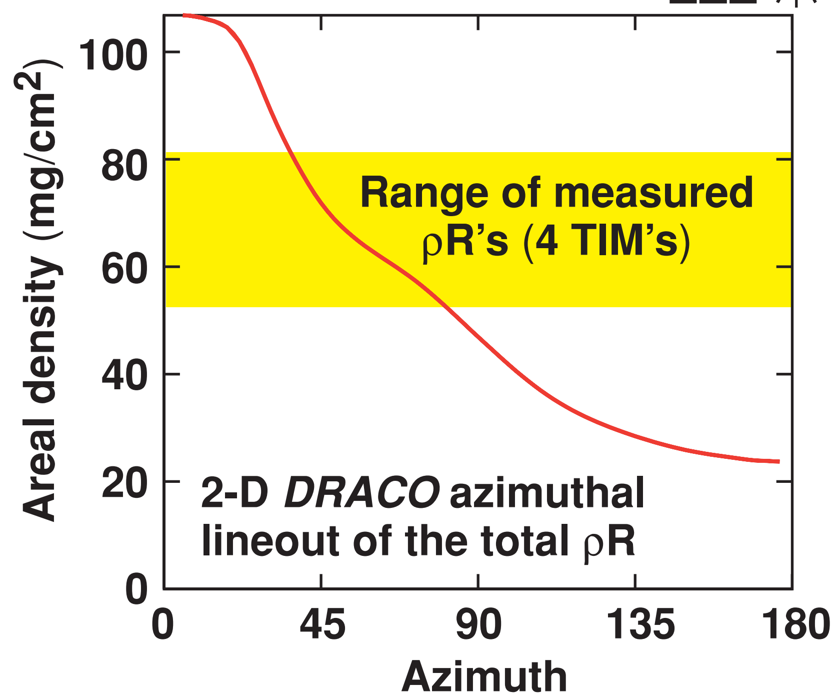
	Expt	1-D	2-D
Y_{1n}	1.27×10^{11}	1.32×10^{11}	7.45×10^{10}
Y_2	1.17×10^{9}	1.40×10^{9}	8.87×10^{8}
<ρR>	61	45	50
T_{ion}	3.6	2.3	2.6

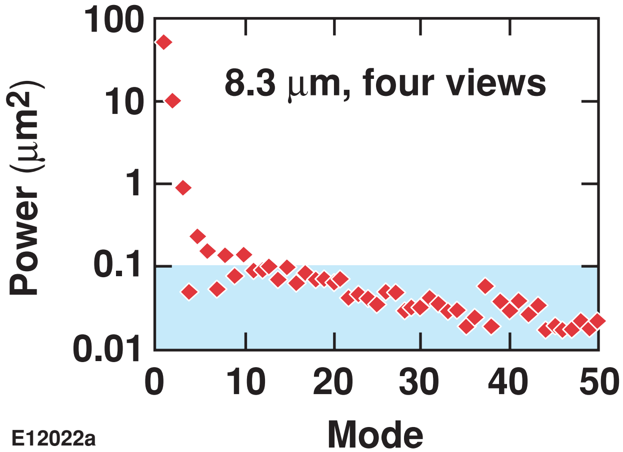
E12021a

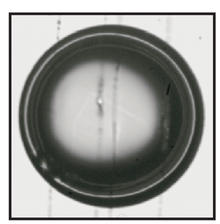
2-D *DRACO* predicts 9% of the 1-D yield for shot 28969 (α ~ 4) while the experimental measurement is 11%

UR LLE









α~4, 11%YOC 28969

	Expt	1-D	2-D
Y_{1n}	5.95×10^9	5.60×10^9	5.32×10^9
Y_2	6.75×10^7	6.94×10^8	6.31×10^7
<ρR>	67	80.0	58
T_{ion}	2.5	1.7	2.0

E12022a

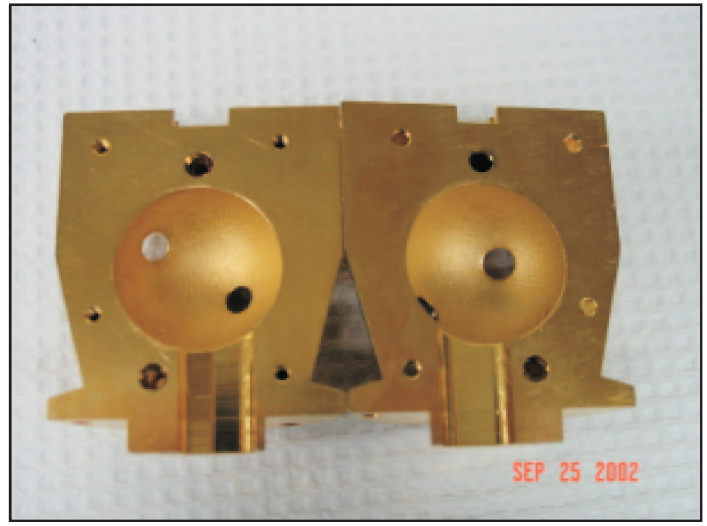
Scaled ignition performance with cryogenic implosions on OMEGA is within reach

UR LLE

Improved ice-layer quality: 1 μm rms

- Feedback on IR power delivered to the layering sphere
- Blast damage to layering sphere
- Vibration mitigation
- MCTC reliability (4× carts)

Layering sphere



Improved laser system uniformity: <1% rms

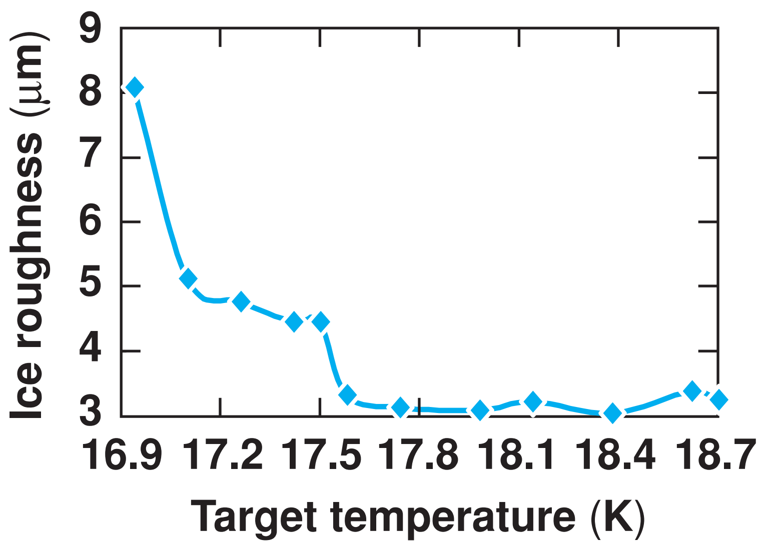
- Target alignment to <10 μm (1% diam)
- Beam pointing
- Power balance
- Beam shape (new DPP's, summer '03)

New diagnostics:

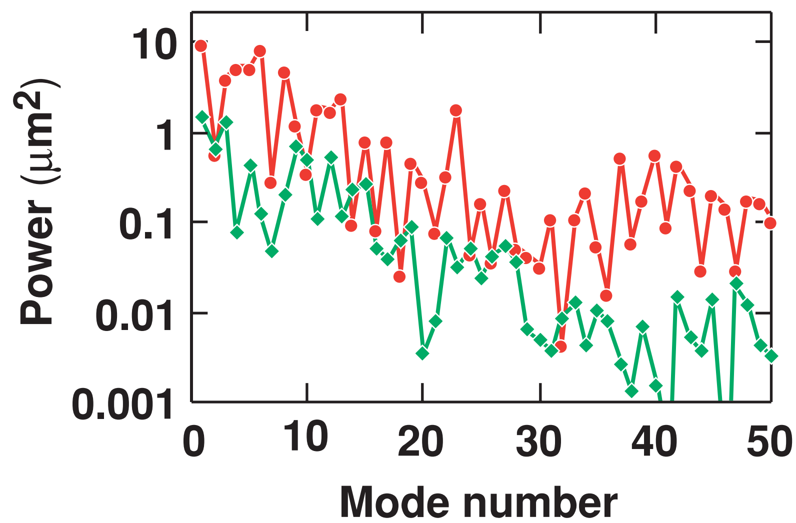
- Stepped wedged range filters (MIT): 4- to 18-MeV proton spectroscopy to measure ρR up to ~250 mg/cm^2
- HSRHOR (LLNL): absolute multispectral absorption spectroscopy to infer hot-spot electron temperature and density
- SHIMG (LLE): differential shell imaging to infer shell areal density modulations

E12024a

The initial ice-layer rms at the triple point can be recovered after cooling 1.8 K



Ice power spectrum after cooling 1.8 K



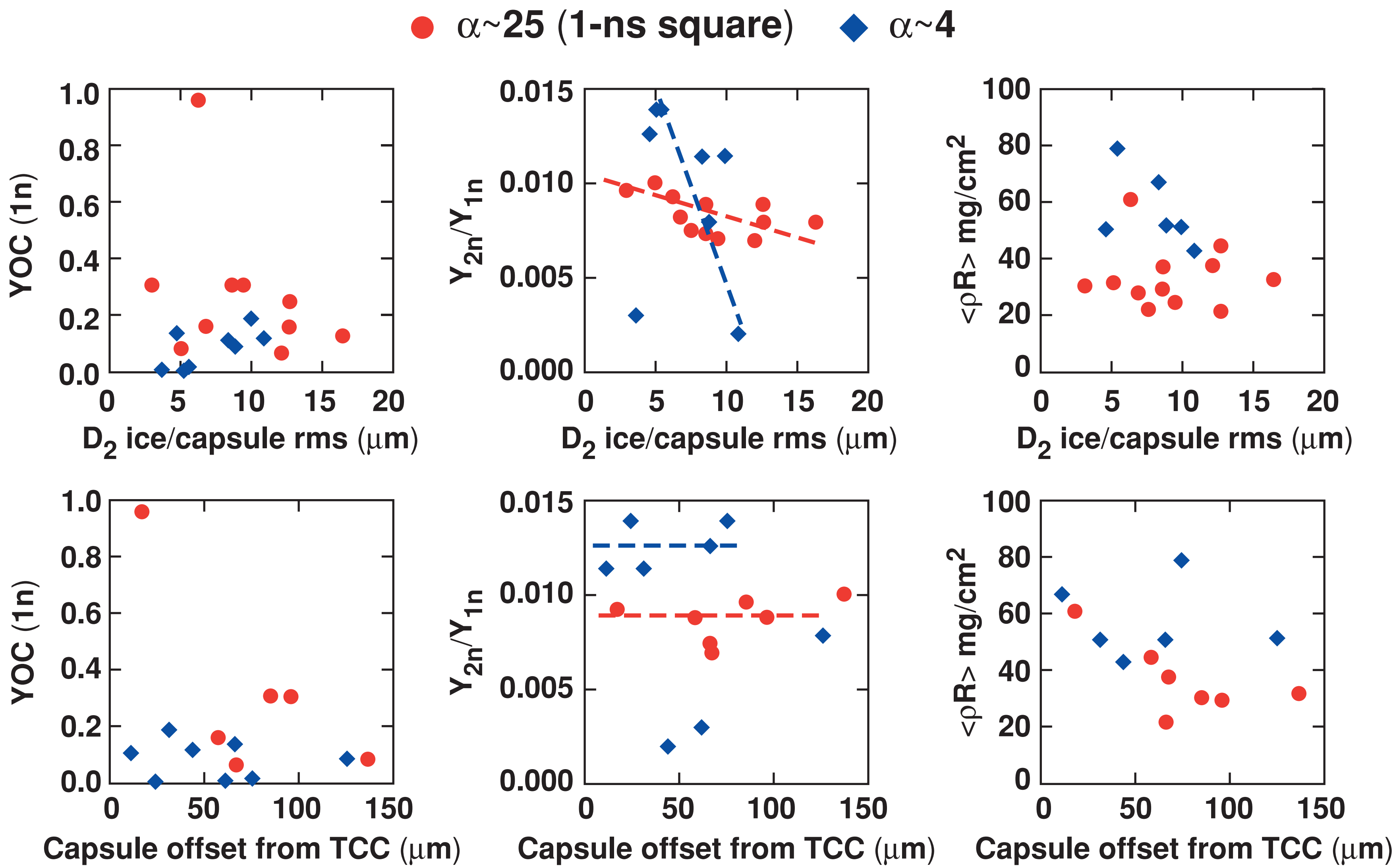
- rms ice roughness at discrete temperatures as target is cooled below the triple point.
- After annealing overnight (17 h), the power spectrum approached the original smoothness.

While layering is performed at the triple point, implosion performance is optimal at a temperature ~ 1.8 K colder.

E12025a

Ignition-Scaled Cryogenic Implosions

The cryogenic data show the expected correlation with D_2 ice roughness and TCC offset



E12063

Analysis of PHC images showed a 60- to 120-μm systematic offset from TCC at the start of the laser pulse

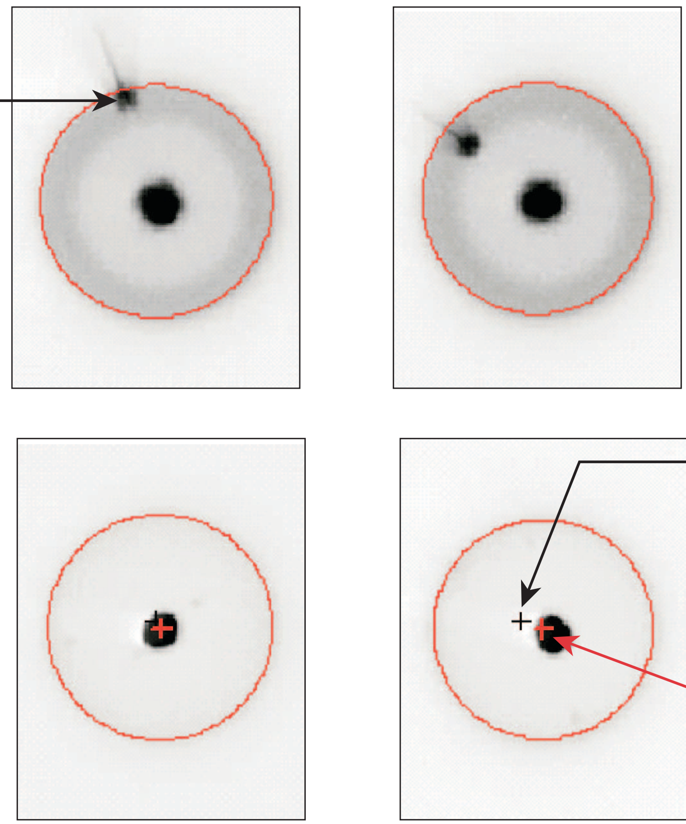
H9 view

H3 view

Shot 26479
(stalk mount)

Measured offset:
d = 85 μm
(θ, ϕ) = 99°, 251°

Shot 26477
(cryo)



TCC defined by stalk-mounted images above

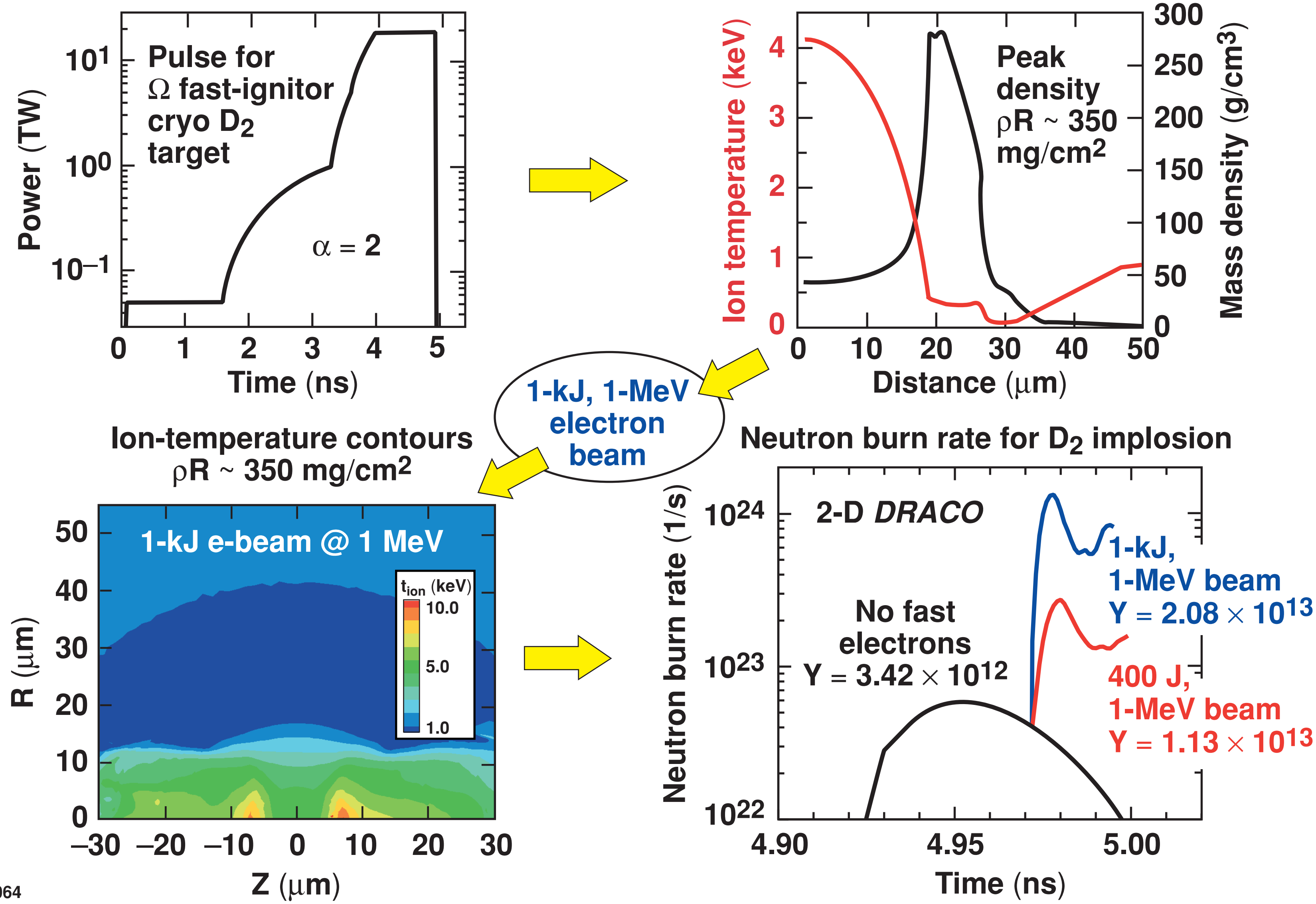
Cryo capsule center at T_0

Note further core offset.

The offset is computed as the average of up to five PHC views on each shot, reducing the errors significantly.

Direct-Drive Fast Ignition

Simulations show that a 1-kJ, 1-MeV electron beam raises the T_{ion} in the high-density fuel shell to ~10 keV



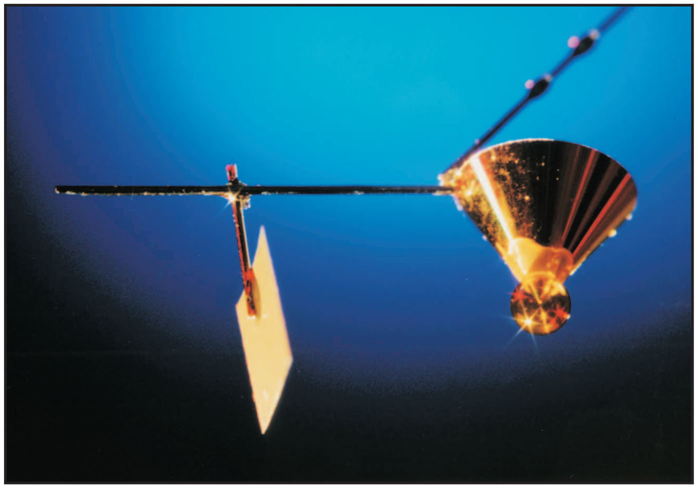
E12064

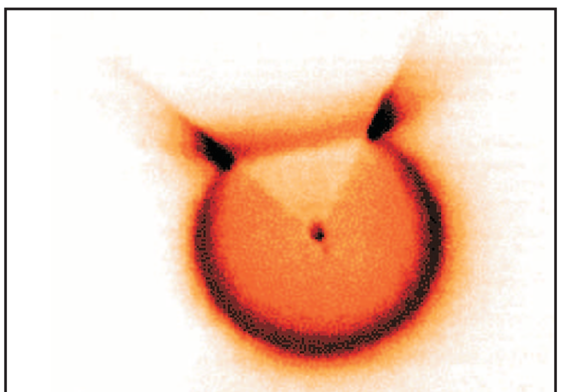
Direct-Drive Fast Ignition

Fuel assembly experiments with cone-focused targets leverage the OMEGA direct-drive program

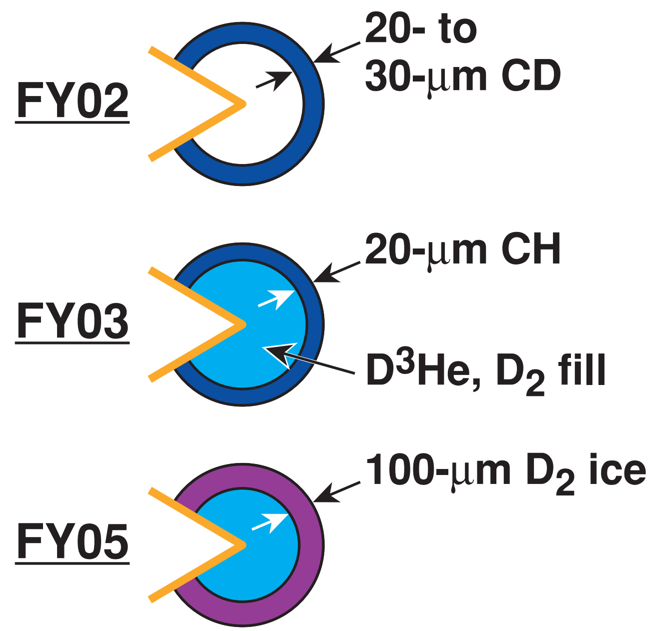
UR LLE

Direct-drive cone targets shot on OMEGA in FY02 (LLNL, GA)





Pinhole camera (H8)

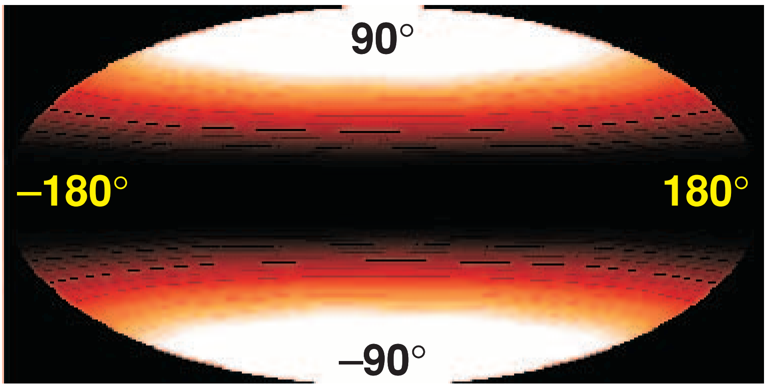


The full suite of OMEGA diagnosics will be applied to these implosions.

E12065

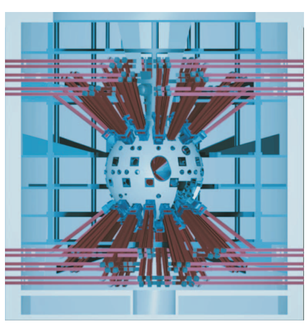
Direct-drive ignition and fast ignition may be possible on the NIF with the indirect-drive beam configuration

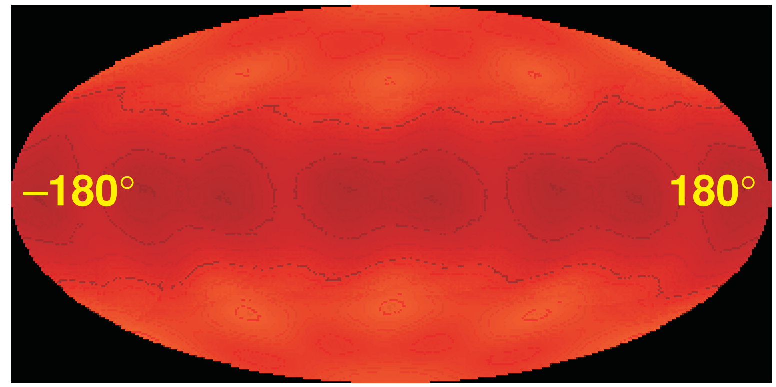
Aitoff projection of intensity on a capsule



σ_{rms} = 48%
peak-to-valley = 157%

NIF direct-drive distribution using 24 (×4) beams in indirect-drive illumination





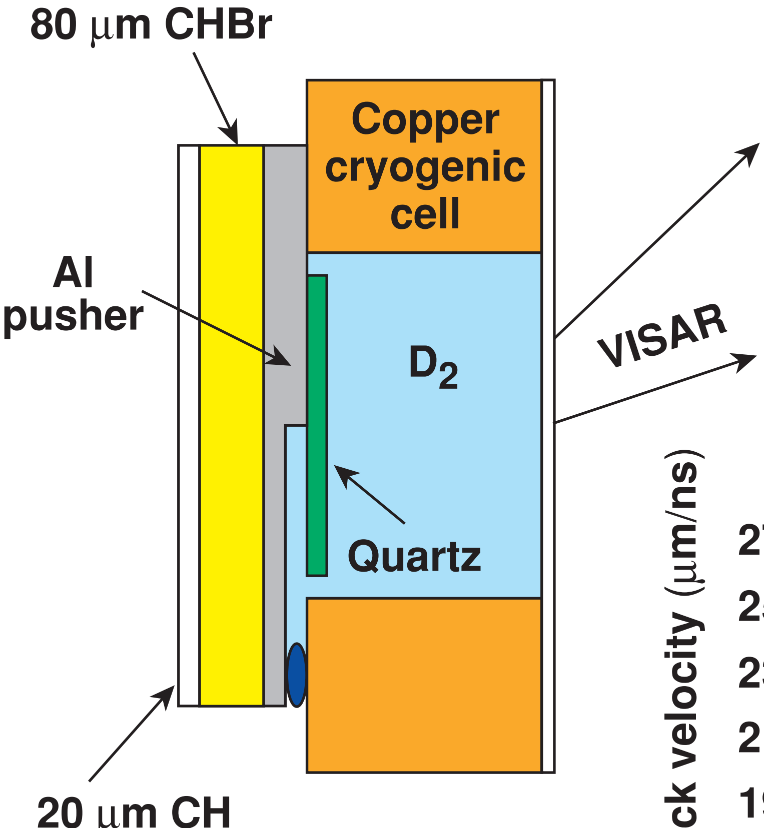
σ_{rms} = 6%
peak-to-valley = 22%

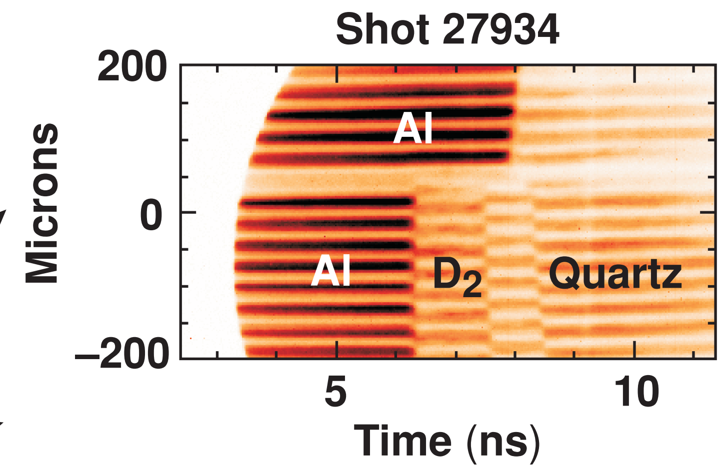
NIF direct-drive intensity distribution with 24 (×4) beams repointed to a pattern similar to OMEGA 24

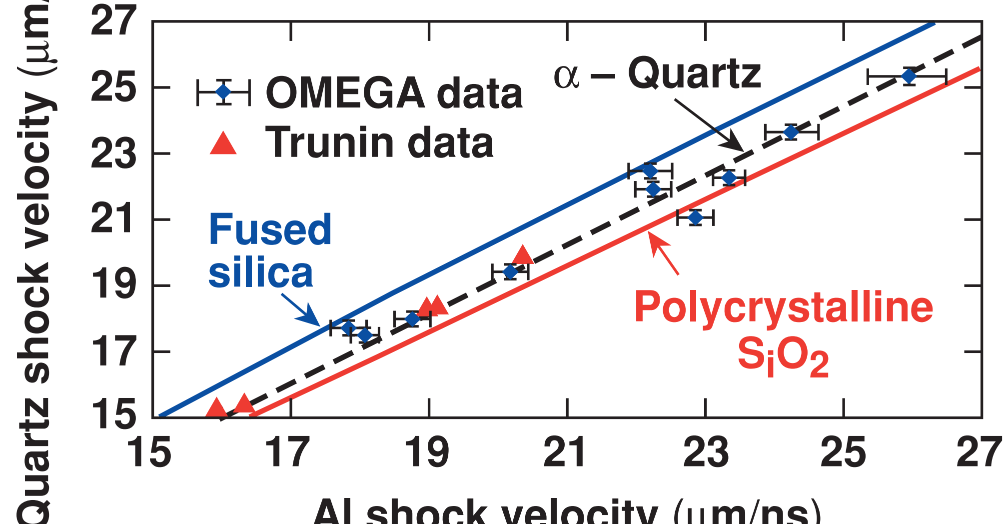
The penalty from asymmetric illumination may be mitigated by the clever use of phase plate design, beam pointing, pulse shaping, and ice layer/capsule shimming.

E11720c

"Diving board" targets provide both impedance match and reshock data on cryogenic deuterium



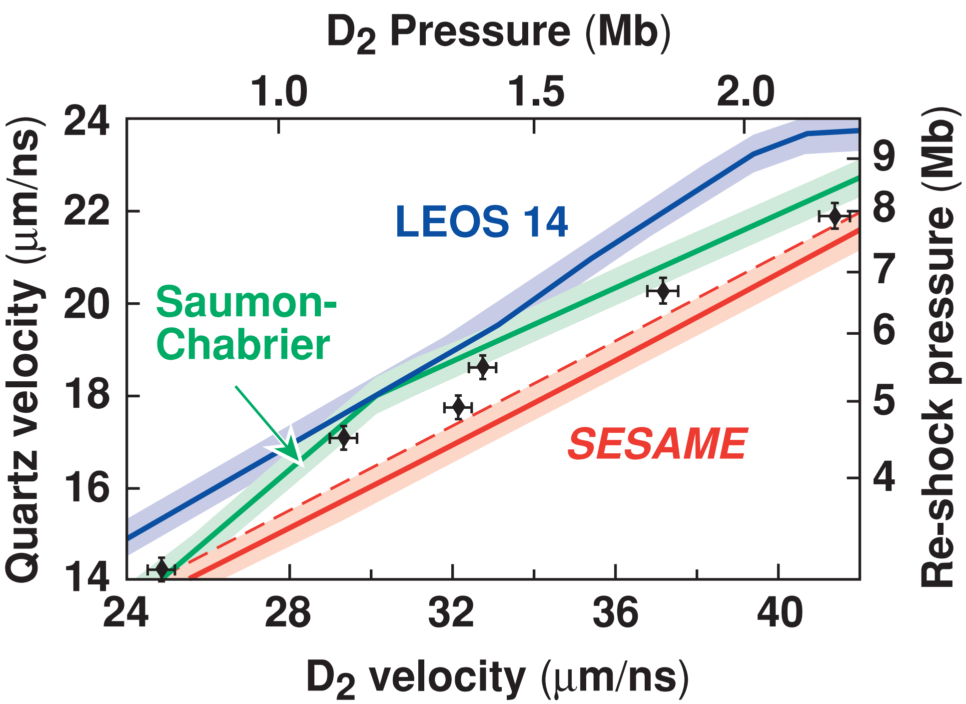


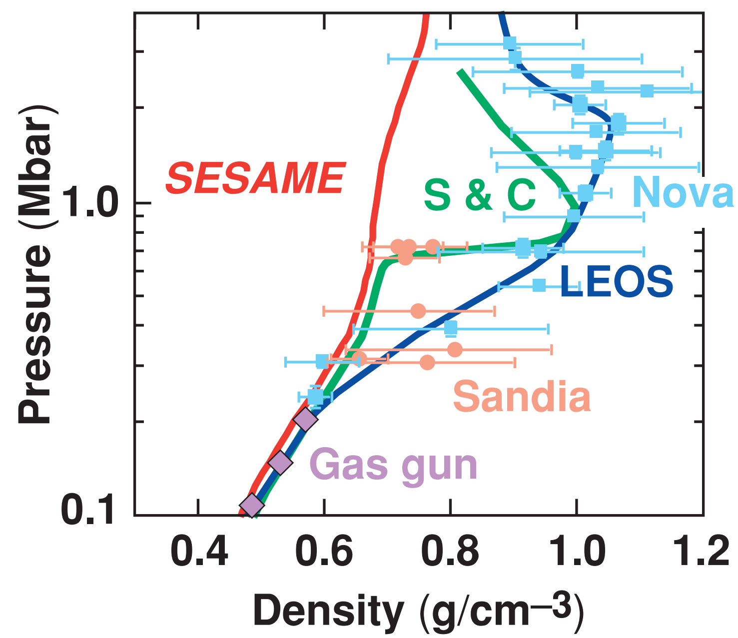


E11829b

D2 EOS

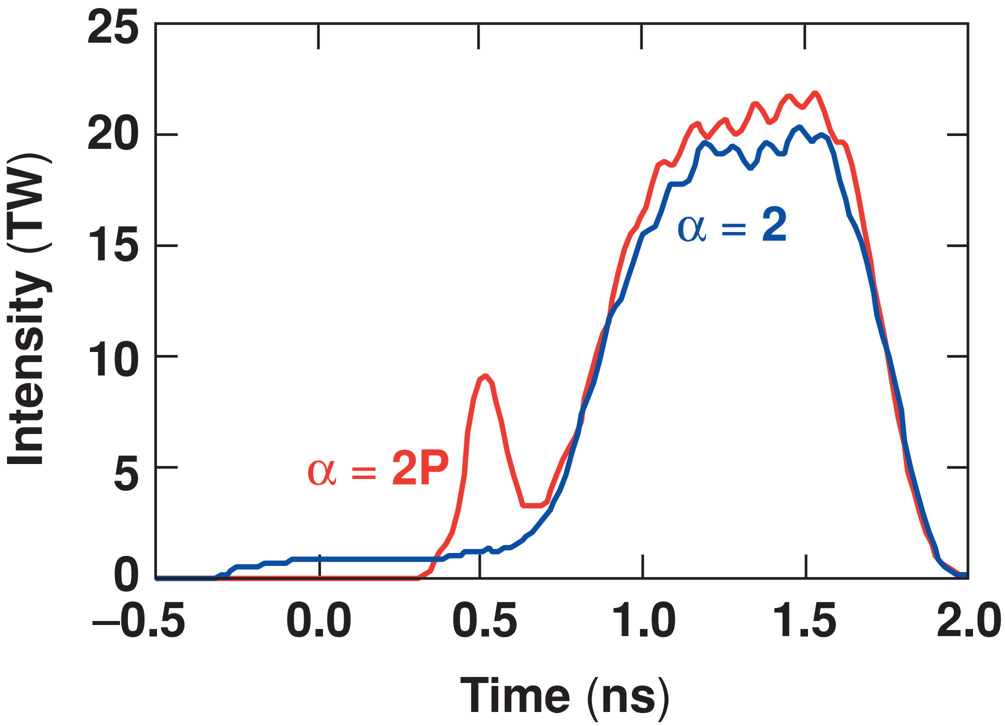
Preliminary data support the compressibility of the Saumon-Chabrier model





E12066

For the initial experiments, a picket was added to an $\alpha = 2$ drive pulse designed for CH shells

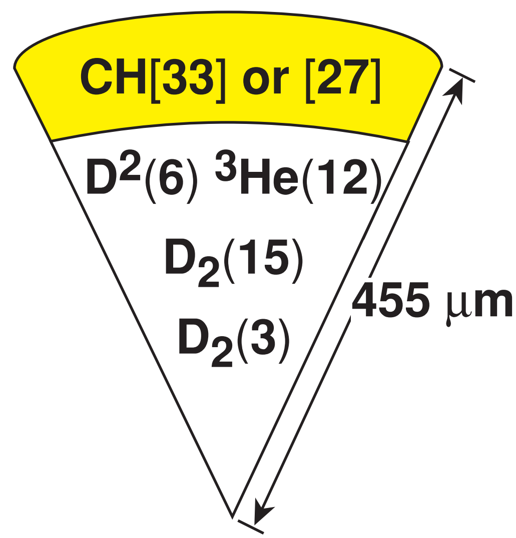


Picket pulse

Width (FWHM) = 120 ps

Amplitude = 0.4 of drive

Position = 340 ps before drive

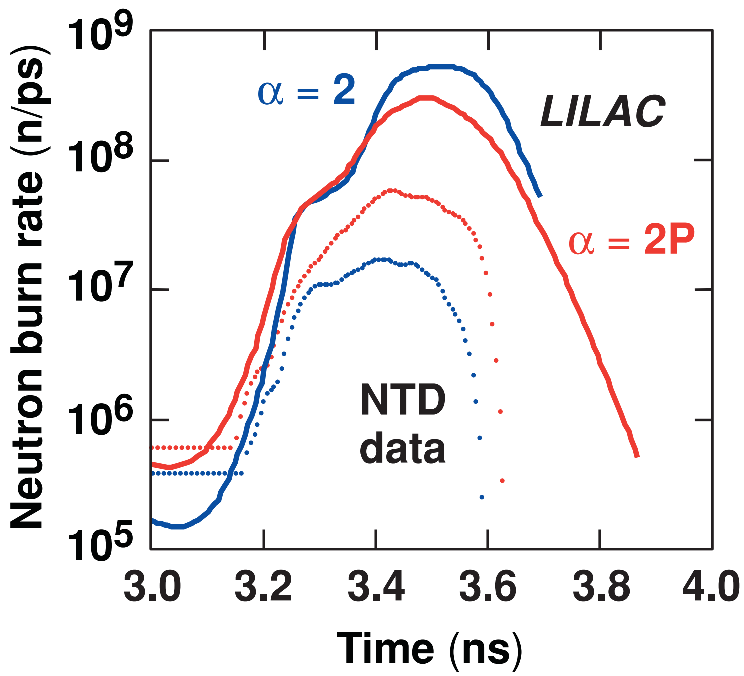


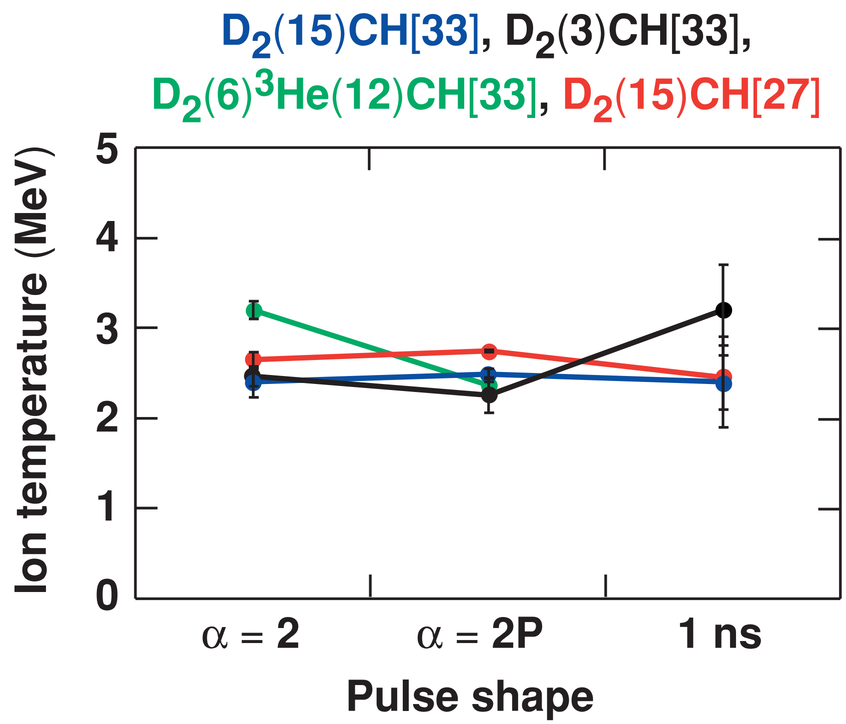
The performance is sensitive to

- picket intensity
- picket FWHM
- picket timing WRT the main drive pulse

E11906a

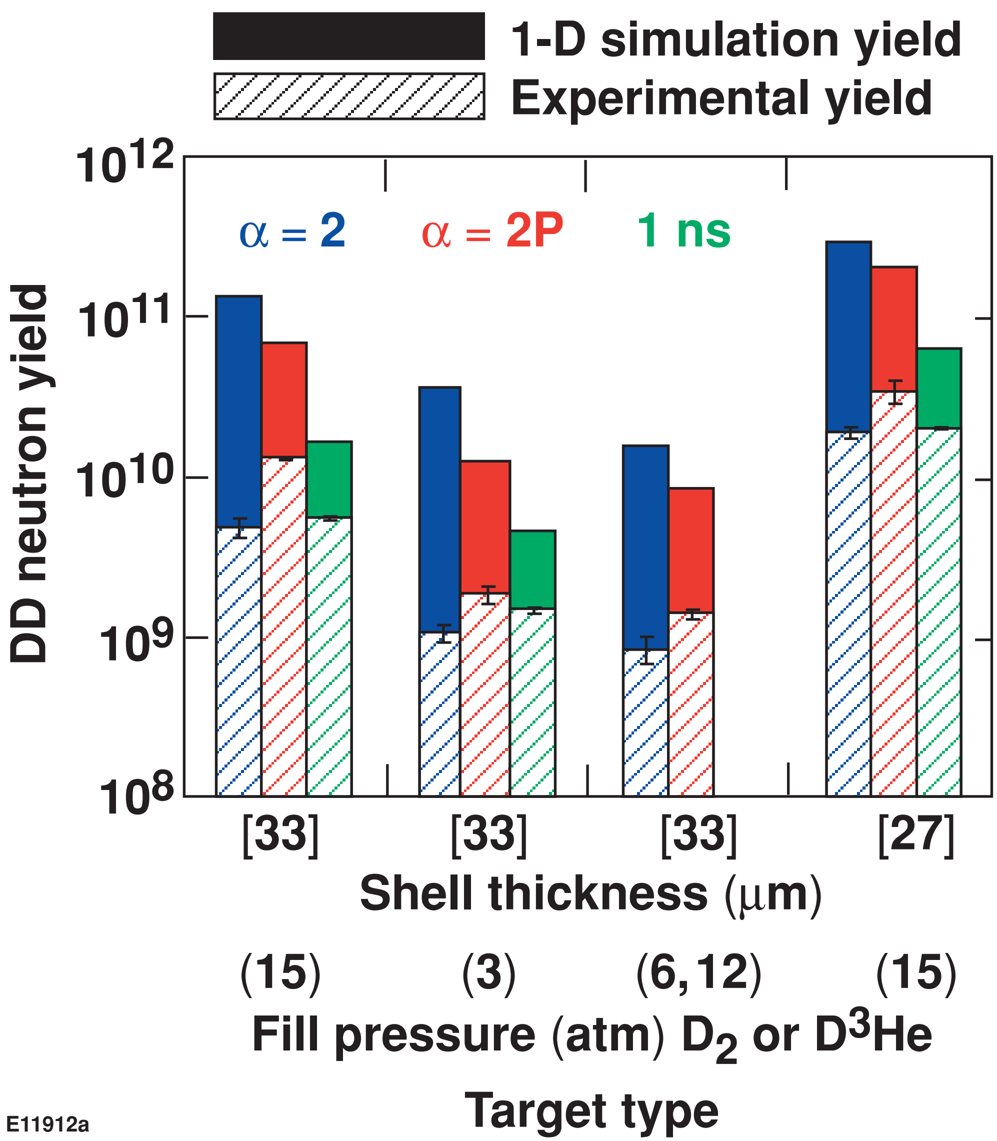
An increase in the neutron burn rate and constant T_{ion} suggest a reduction in mix with the picket pulse

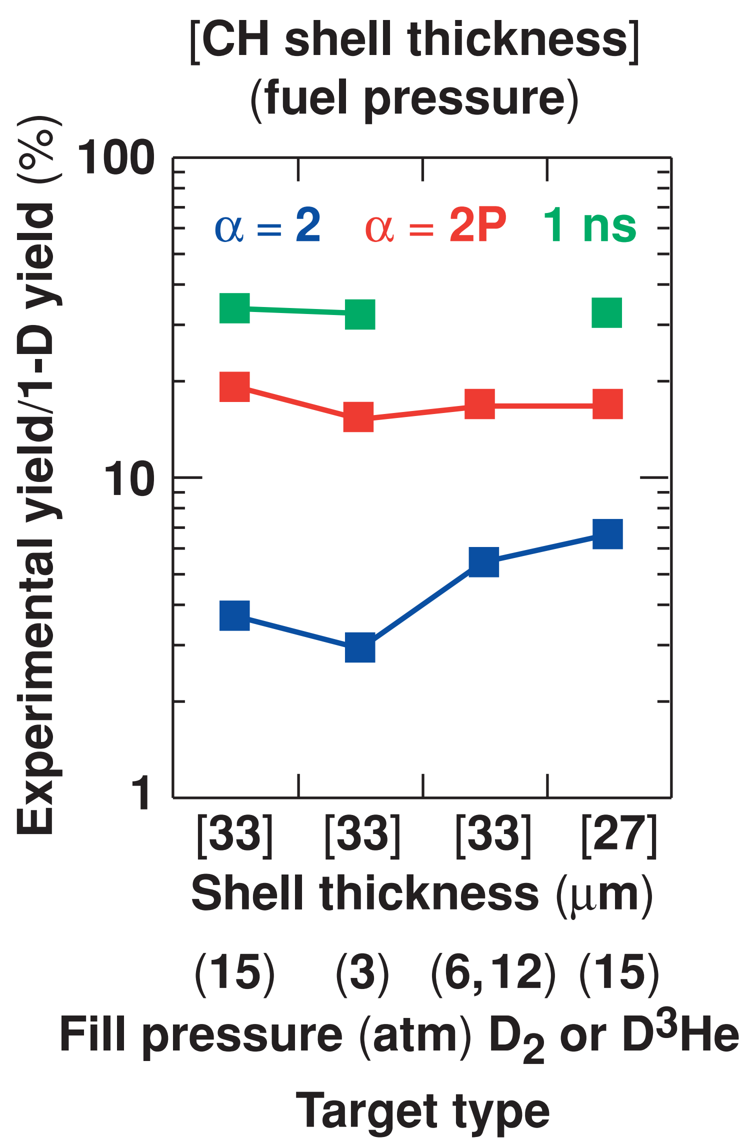




Adiabat Shaping

Both the experimental yield and the normalized yield (clean 1D) increase when a picket pulse is used





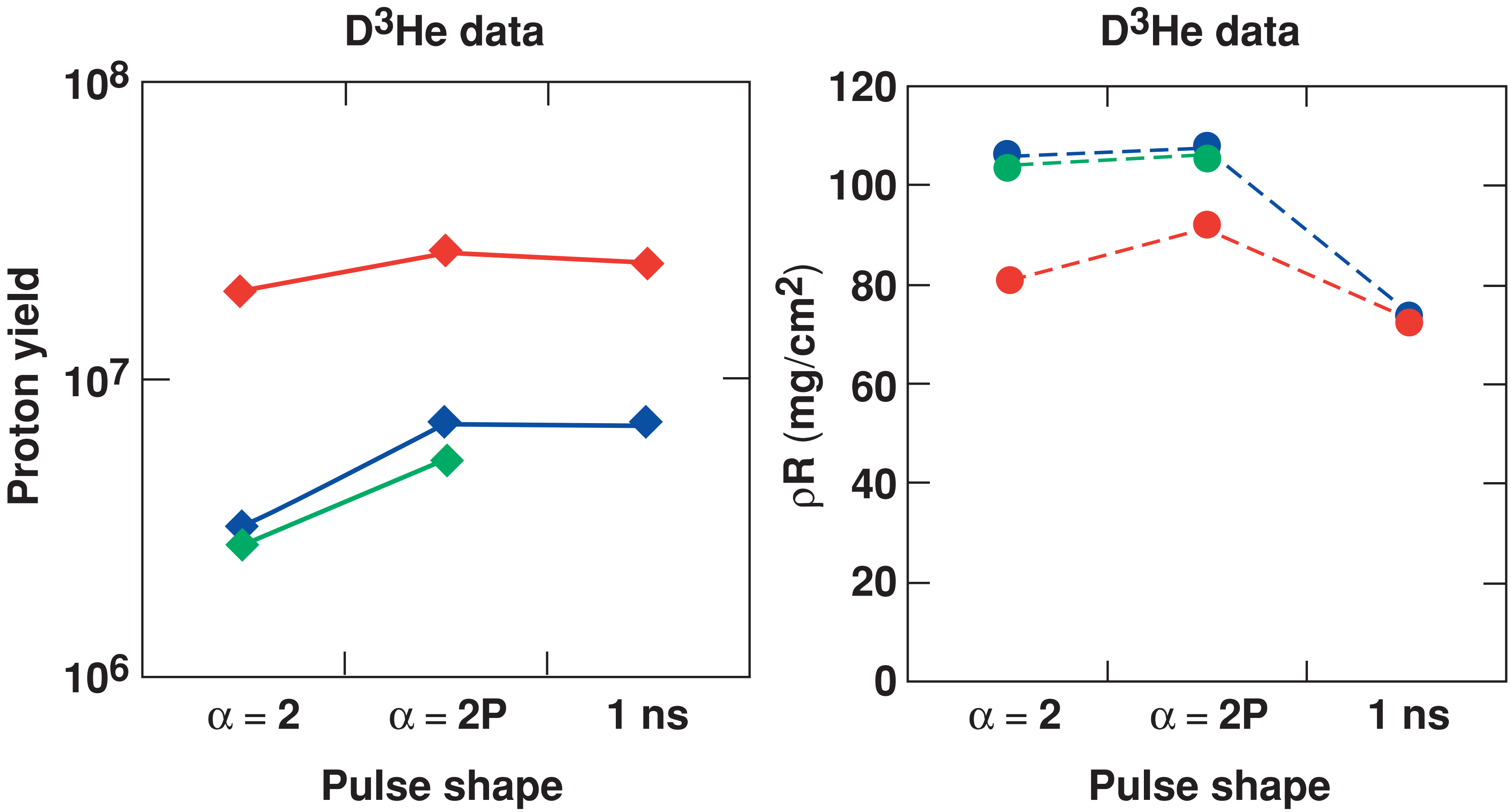
E11912a

Adiabat Shaping

The picket increases the yield from D^3He filled capsules with similar compressibility

UR LLE

$D_2(15)CH[33]$, $D_2(6)^3He(12)CH[33]$, $D_2(15)CH[27]$



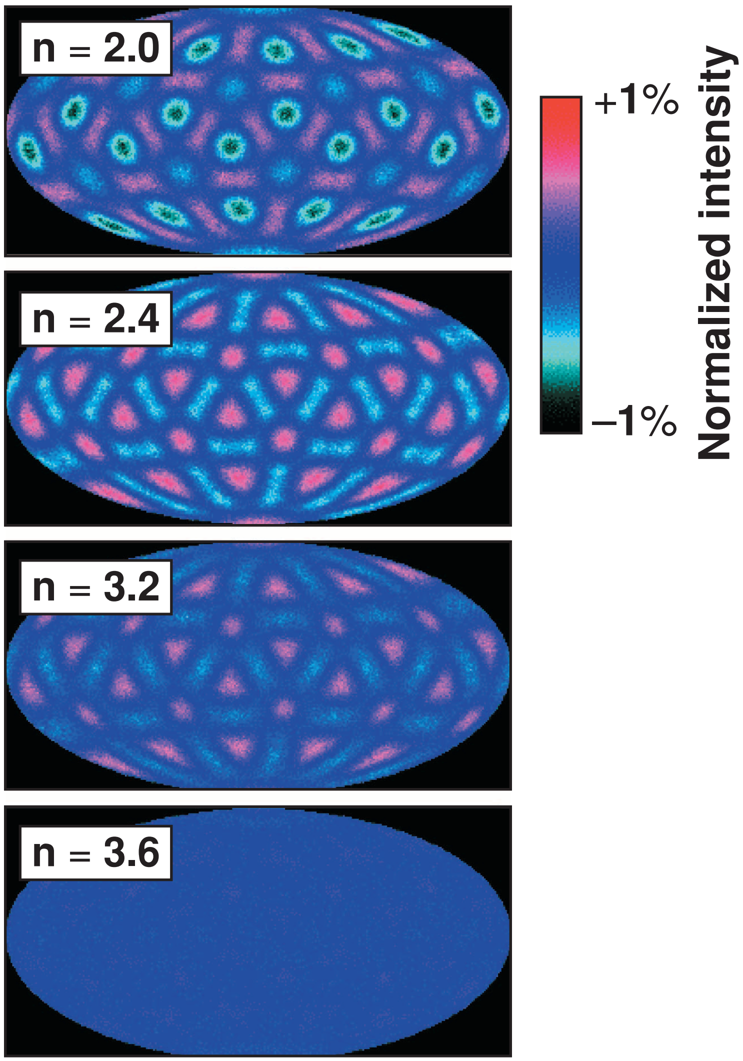
E11913a

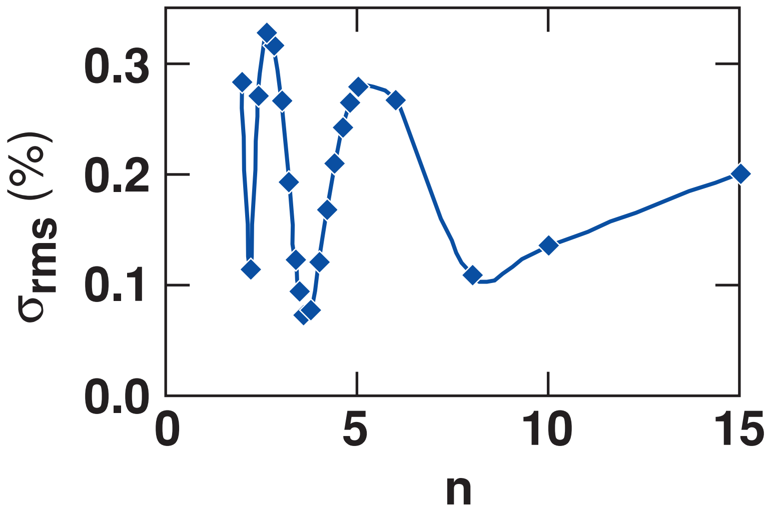
Reduced Laser Nonuniformity

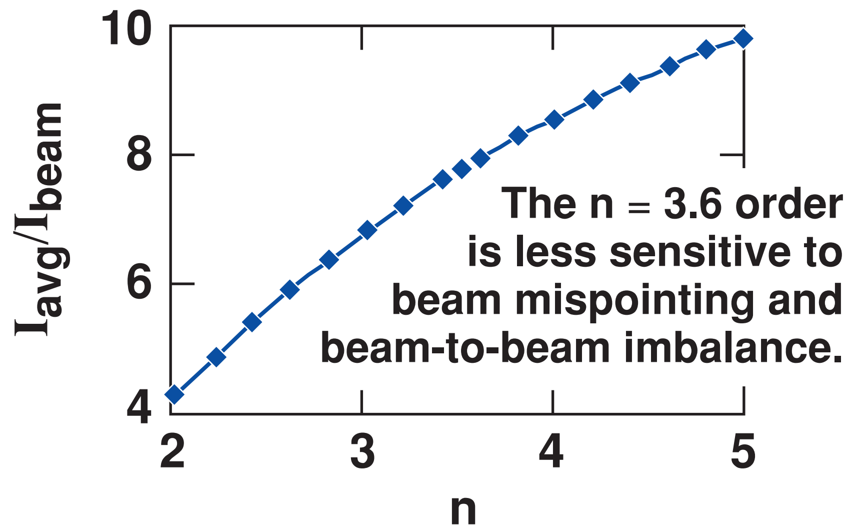
New DPP's with an n = 3.6 super-Gaussian profile will significantly improve the laser uniformity

UR LLE

$$I = I_0 \times e^{-(r/r_0)^n}$$







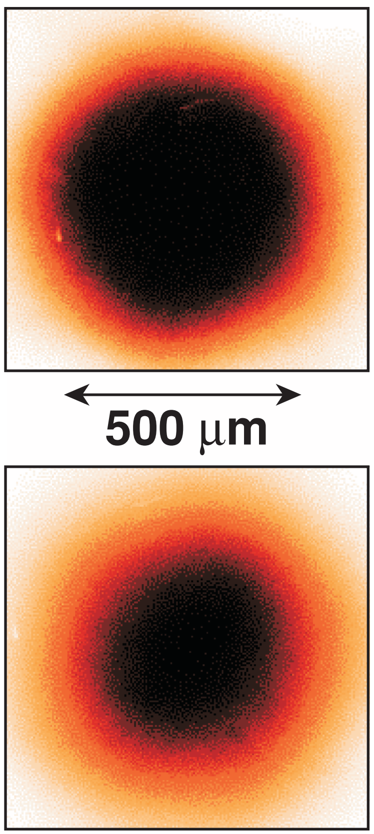
E12068

Reduced Laser Nonuniformity

The new DPP design will immediately improve the direct-drive illumination uniformity on OMEGA

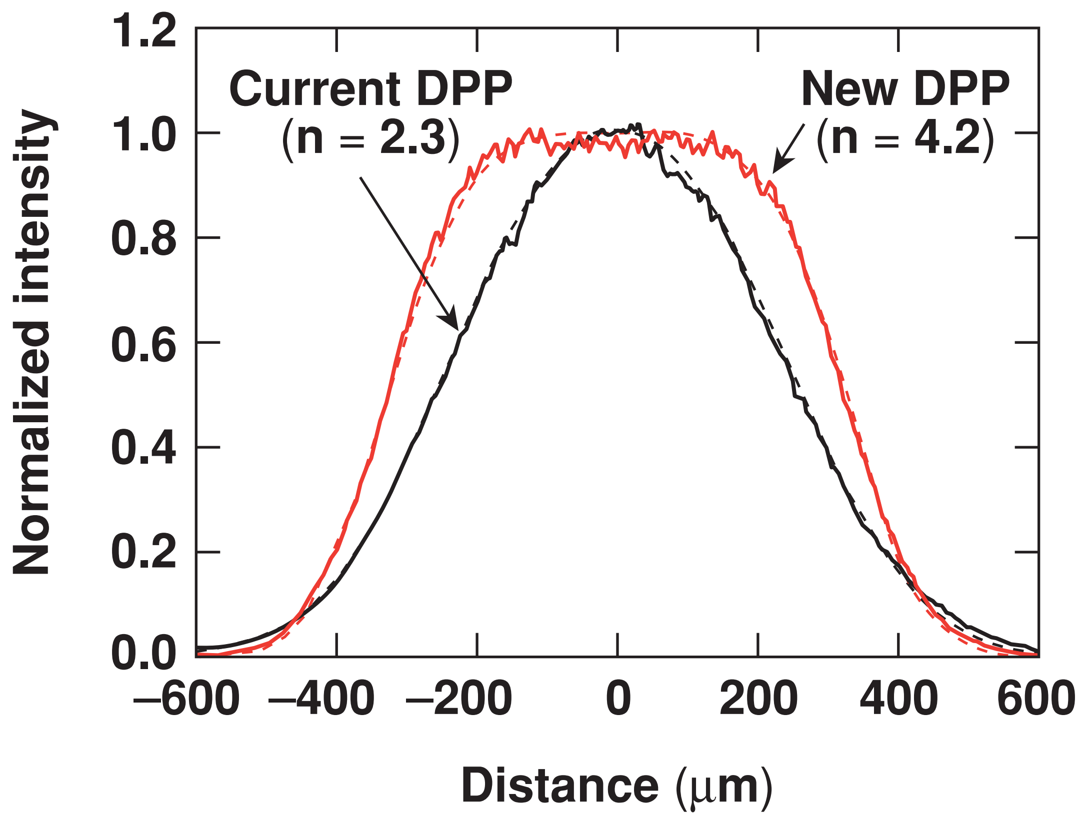
UR LLE

ETP images
New DPP (n = 4.2)



Current DPP (n = 2.3)

Horizontal lineouts through ETP's
(best fits are dashed lines)



E11994a

Optimized beam shape significantly reduces low-ℓ-mode contributions to laser nonuniformities

UR LLE

σ_{rms} contributors

	Beam shape	Beam pointing	Beam balance	TOTAL
Current DPP's (n = 2.3)	1.1%	1.9%	1.3%	2.6%
New DPP's (n = 4.2)	0.6%	0.6%*	0.4%†	0.9%

* Requires precision beam pointing (≤ 10 μm rms)
† Requires precision beam balance (≤ 2% rms)
All values are time averaged assuming 1-THz SSD conditions.

E11999a