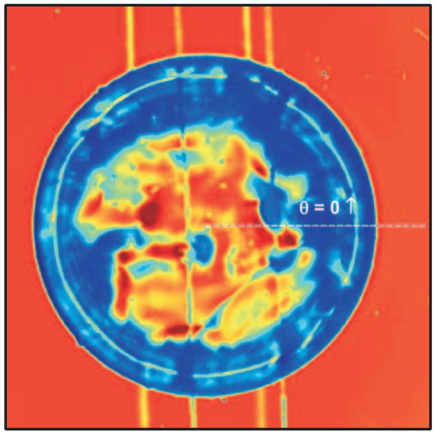
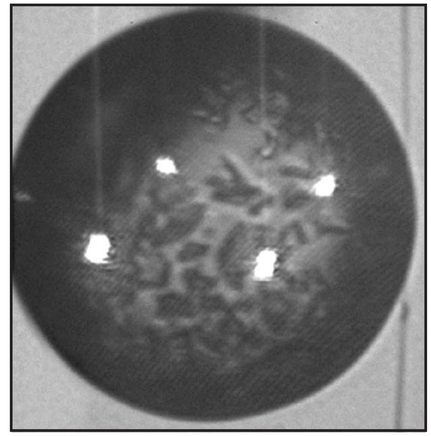
Direct-Drive Cryogenic Target Implosion Performance on OMEGA





Shot 33687 Experimental ($\alpha \sim 4$)	YOC	Shot 33220 Experimental ($\alpha \sim 40$)	YOC
Yield (1n): 4.6×10^9 TCC offset: 36 μm	23%	Yield (1n): 1.78×10^{11} 40 μm	~115%

P. W. McKenty
University of Rochester
Laboratory for Laser Energetics

45th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Albuquerque, NM
27–31 October 2003

The OMEGA cryogenic implosion campaign is a staged program leading to verification of scaled-ignition performance with DT fuel by the end of FY05

- The program is driven by three main objectives:
  - Validation of target performance for the lowest effective adiabat
  - Minimization and absolute characterization of DT cryogenic-layer roughness
  - Use of cryogenic DT targets in OMEGA implosion experiments

Summary

Recent improvements in critical areas of direct-drive uniformity have OMEGA beginning to demonstrate scaled-ignition performance of cryogenic implosions

- Adiabat-shaping techniques allow the fielding of lower-adiabat-implosion experiments on OMEGA.
- Extensive research and development have produced ice-layer finishes approaching the 1-μm NIF requirement.
- The cryogenic DT Fill and Transfer Station (FTS) is currently being qualified, and DT layering and fractionation studies will commence by the end of FY04.

For targets at TCC, 2-D *DRACO* simulations agree with experimental observations.

Collaborators

T. C. Sangster, M. Alexander, R. S. Craxton, J. A. Delettrez, L. M. Elasky,
R. Epstein, A. Frank, V. Yu. Glebov, D. R. Harding, S. Jin, J. P. Knauer,
R. L. Keck, S. J. Loucks, L. D. Lund, R. L. McCrory, F. J. Marshall,
D. D. Meyerhofer, S. F. B. Morse, S.P. Regan, P. B. Radha, S. Roberts,
W. Seka, S. Skupsky, V. A. Smalyuk, J. M. Soures, and M. Wozniak

Laboratory for Laser Energetics
University of Rochester

J. Frenje, C. K. Li, R. D. Petrasso, F. H. Séguin

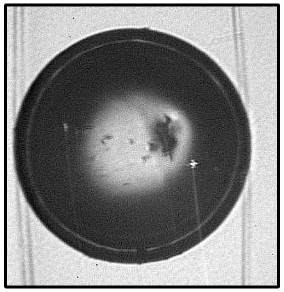
Plasma Science and Fusion Center
Massachusetts Institute of Technology

N. Izimui, J. A. Koch, R. A. Lerche, M. J. Moran, T. W. Phillips,
G. W. Schmid, C. Sorce, and A. Warwick

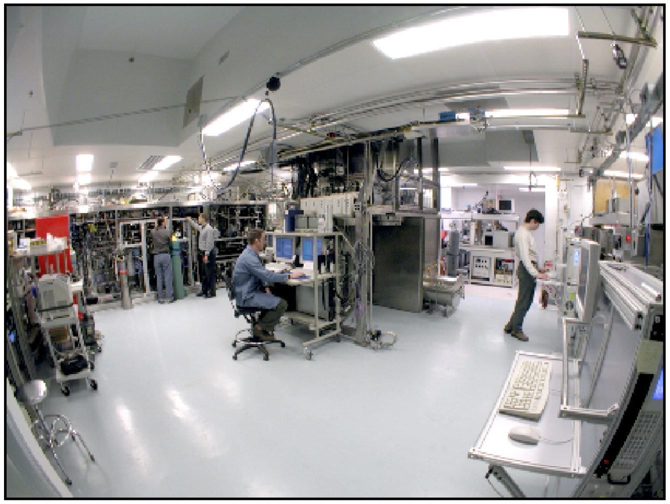
Lawrence Livermore National Laboratory

Cryogenic target implosions require significant engineering and development

- Cryogenic implosions have been carried out on OMEGA for ~3 years.
- Significant obstacles have been overcome:
  - cryogenic target transport
  - target survival
  - target-layer survival



- Target vibration at shot time has been minimized.



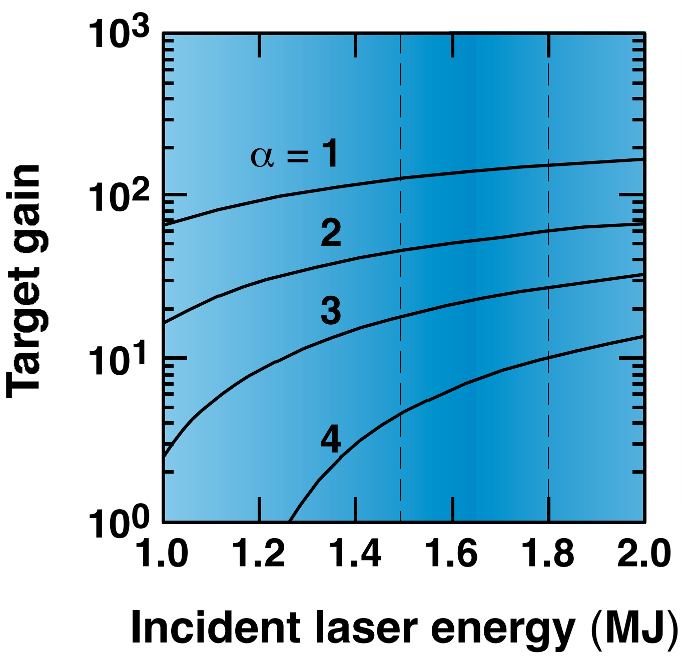
Bottom line: Fielding cryogenic targets is very difficult and requires a lot of time and effort.

I1420b

Direct-drive ICF has traditionally traded target performance for increased hydrodynamic stability

$$\alpha = \frac{\text{Fuel specific energy}}{\text{Fermi-degenerate specific energy}}$$

UR/LLE 351-nm direct-drive gain curves

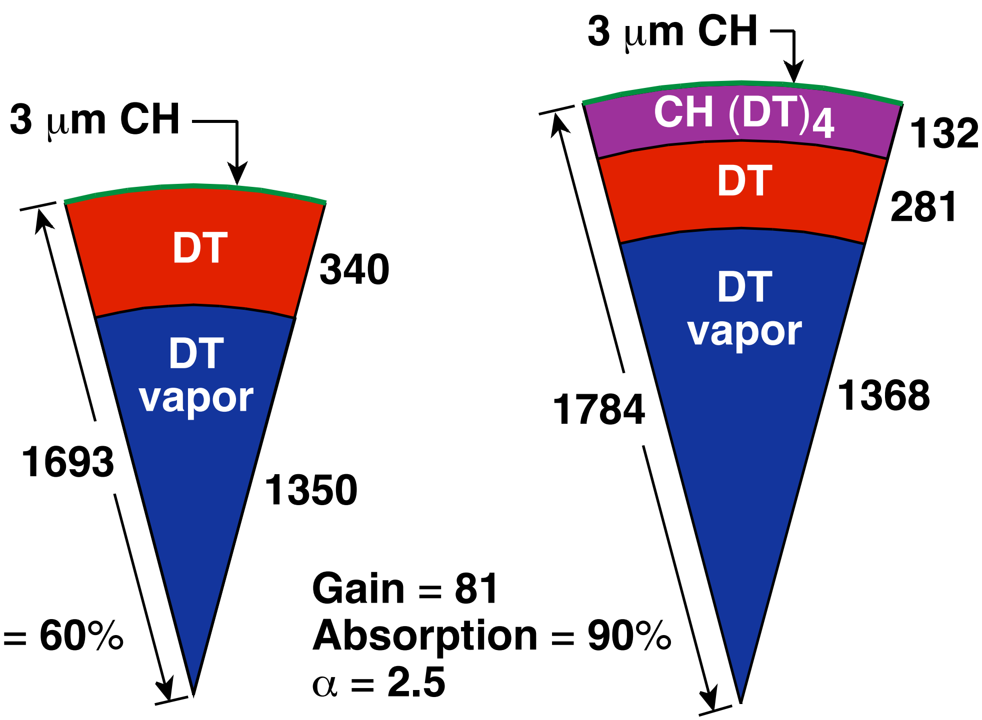


Hydrodynamic and laser–plasma instability constraints will determine the performance of NIF ICF capsule implosions.

	Instabilities	
Direct drive	Hydrodynamic	Laser–plasma
Indirect drive	Hydrodynamic	Laser–plasma

TC3953f

OMEGA cryogenic implosion campaign is examing scaled-ignition NIF target designs employing two ablator concepts



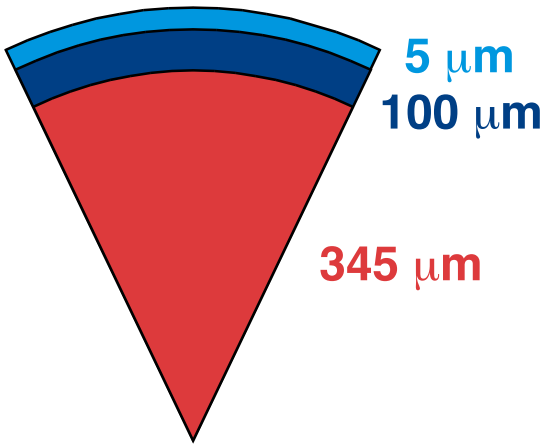
Gain = 45
Absorption = 60%
α = 3

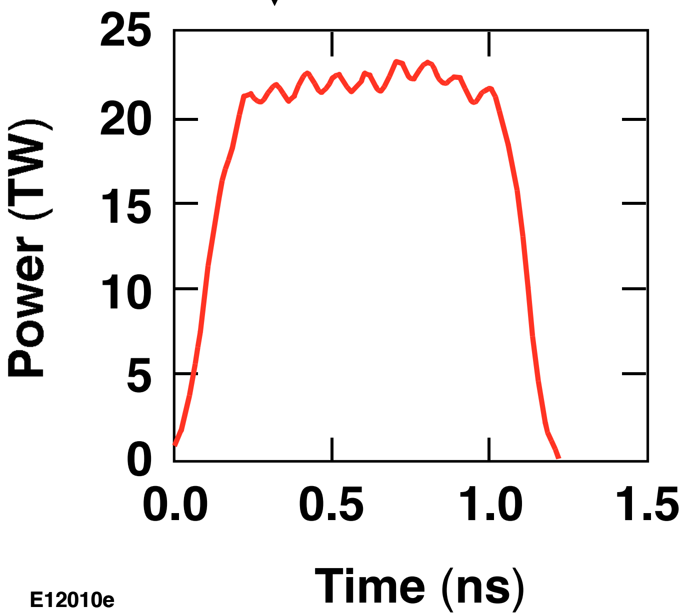
"All-DT"

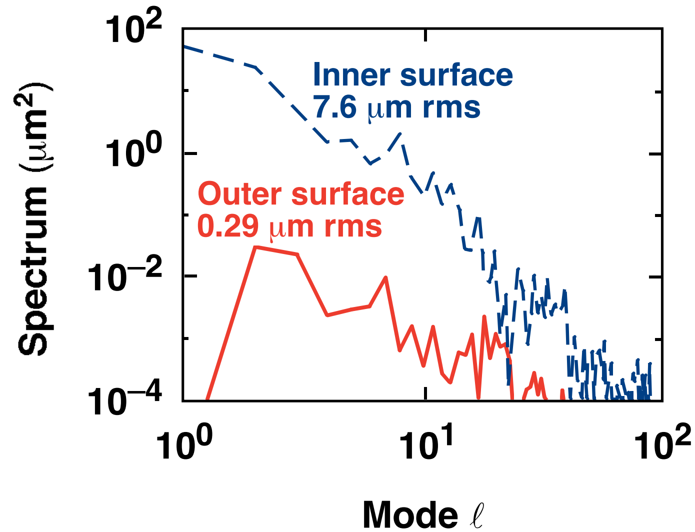
Gain = 81
Absorption = 90%
α = 2.5

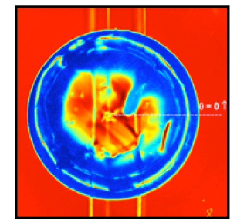
"Wetted-foam"

Initial cryogenic implosion experiments use high-adiabat pulses to probe the effect of ice roughness on target performance

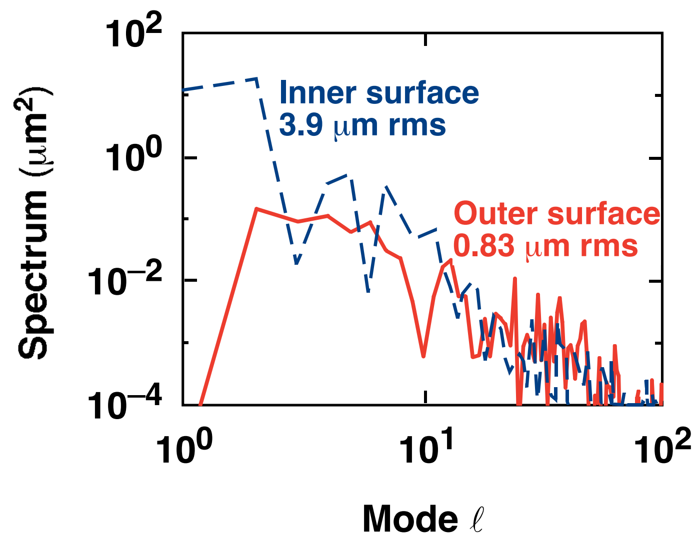


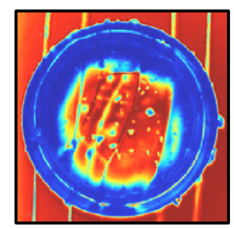






$\alpha \sim 25$,
27% YOC
33413

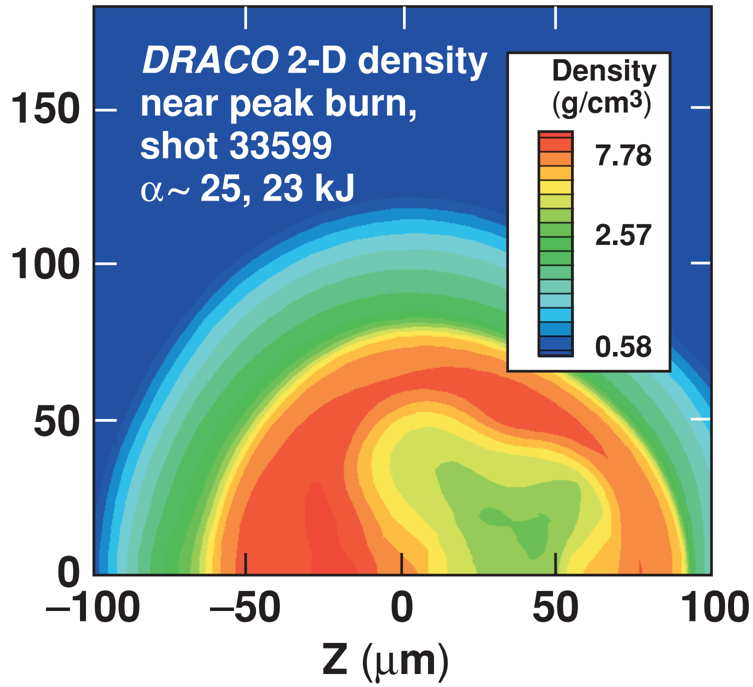


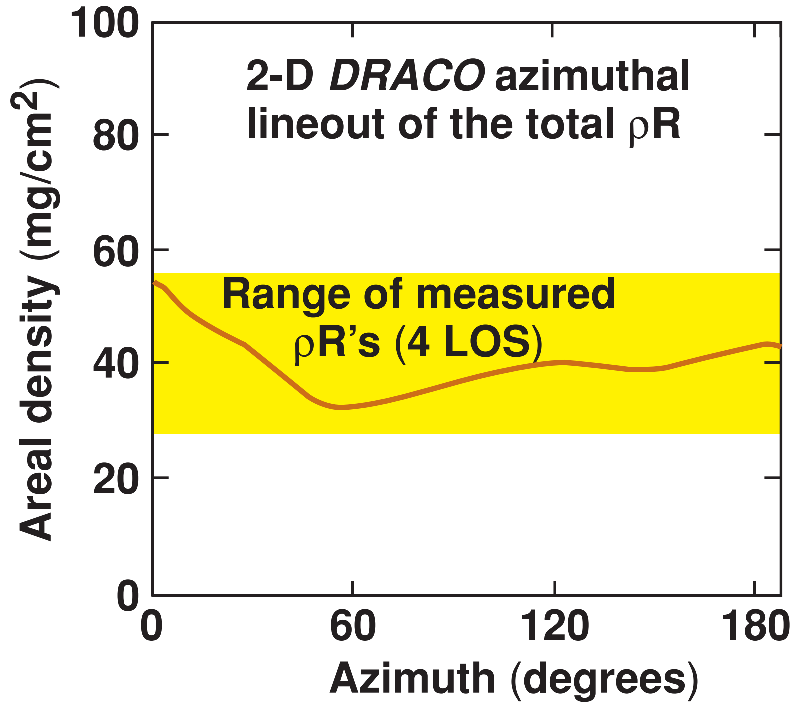


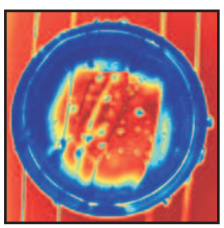
$\alpha \sim 25$,
36% YOC
33599

E12010e

2-D *DRACO* accurately predicts performance and core conditions for shot 33599 ($\alpha \sim 25$)







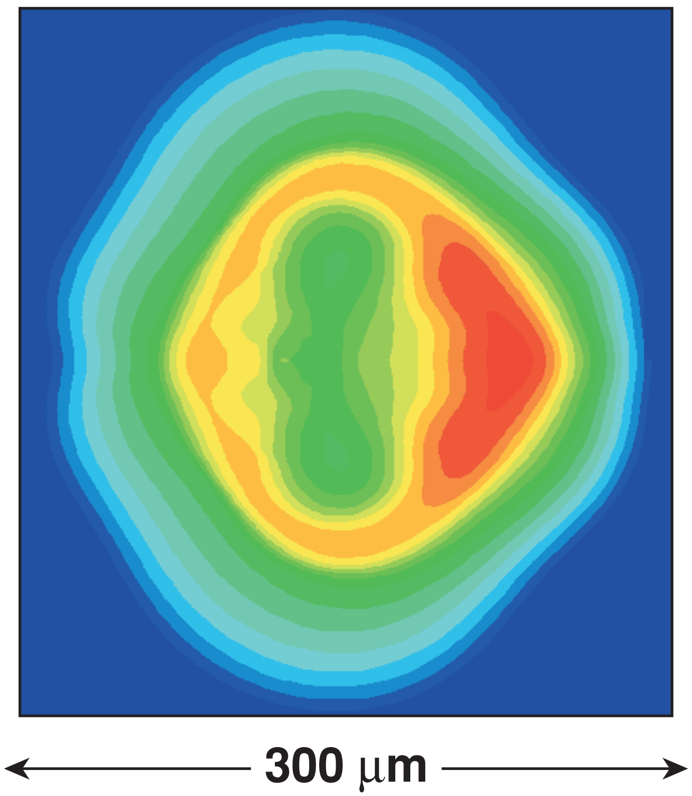
1 ns,
26% YOC
33599

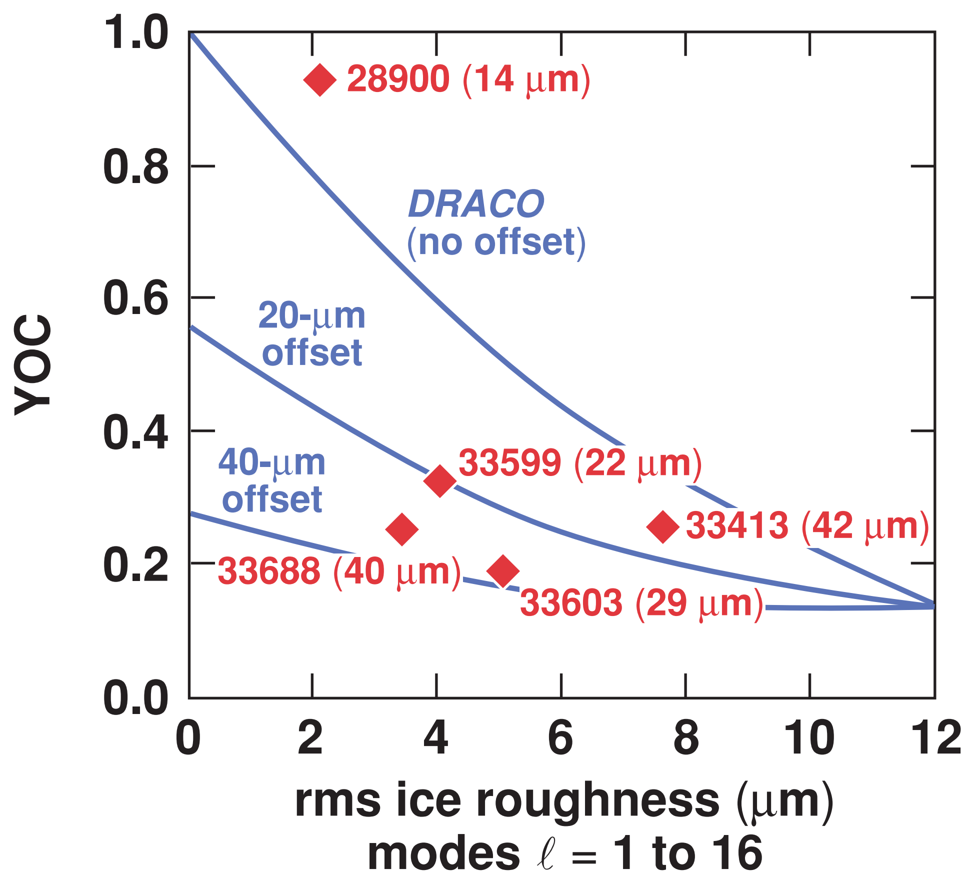
	Expt	1-D	2-D
Y_{1n}	6.49×10^{10}	1.84×10^{11}	6.86×10^{10}
Y_{2n}	6.86×10^{8}	1.90×10^{9}	6.92×10^{8}
$\langle \rho R \rangle$	49	38	52
T_{ion}	2.9	2.6	2.0

TC6462

Comparisons between experimental results and 2-D *DRACO* simulations demonstrate good agreement for high-adiabat implosions

Shot 33413



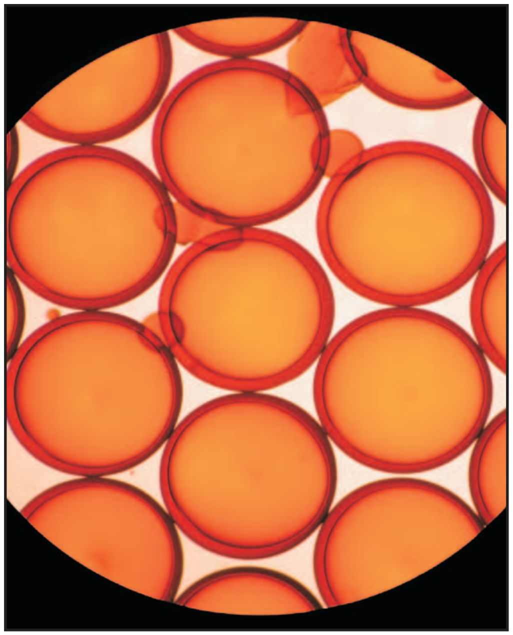


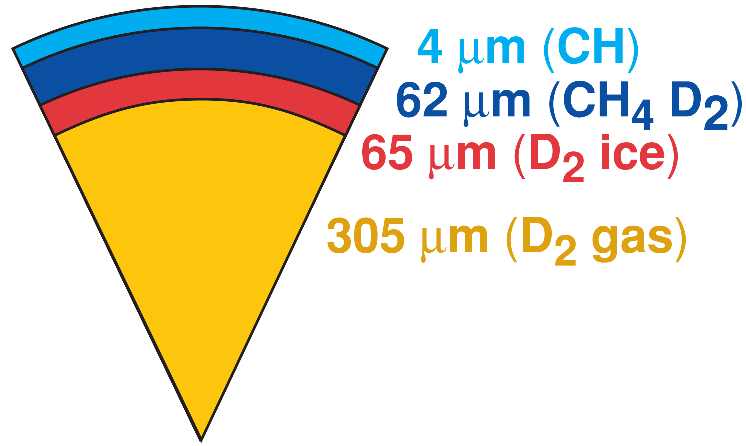
TC6108a

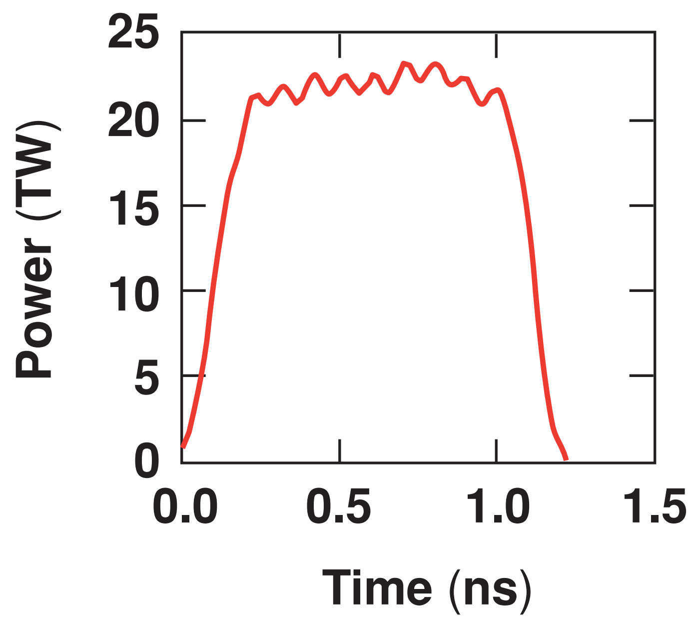
Research at GA has produced a variety of dry foams for ICF implosion experiments on OMEGA

GENERAL ATOMICS

R/F foam
shells in liquid







TC6464

Accurate modeling of shock transit is critical in the design of wetted-foam ignition targets

UR LLE

- 1-D and 2-D simulations of wetted-foam designs generally assume a homogeneous mixture for the wetted-foam layer.
- Does this assumption change the simulated shock speeds?

AMRCLAW[1] simulation of shock transit through a wetted-foam matrix

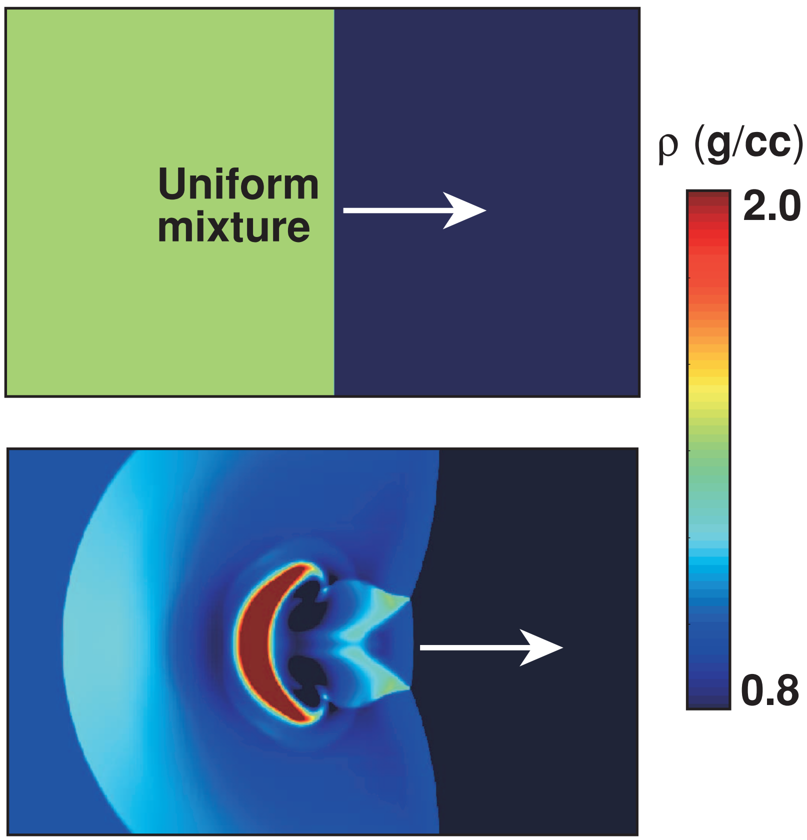
[1] Adam Frank, University of Rochester, Department of Physics and Astronomy
Reference: http://www.pas.rochester.edu/~afrank/theory/index.html

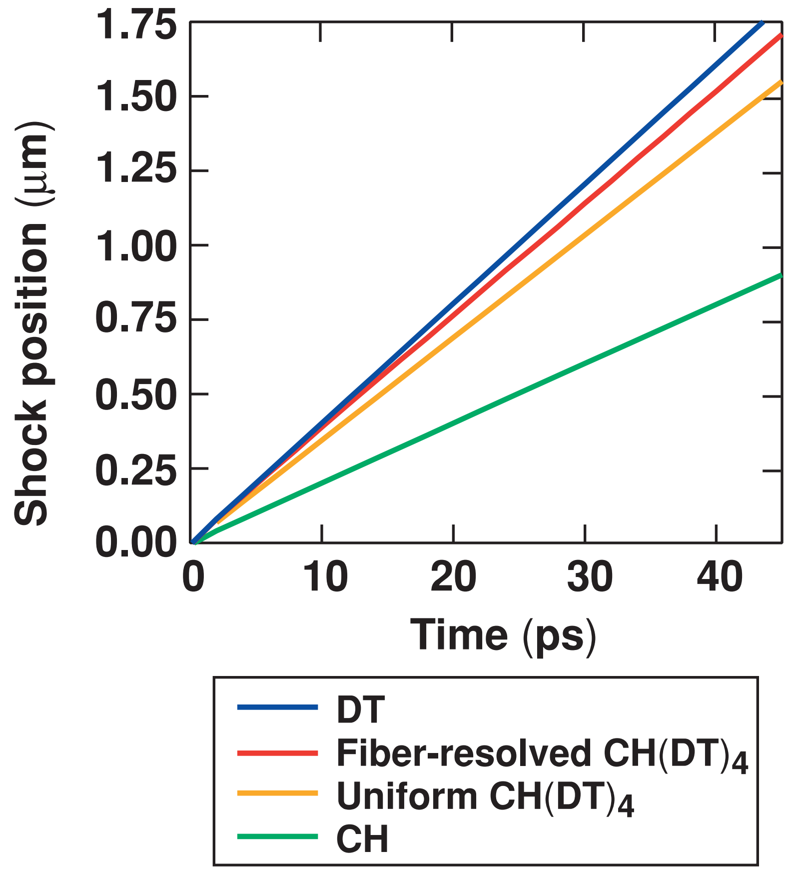
TC6303a

The higher shock speed in DT more than compensates for the lower shock speed in CH

UR LLE

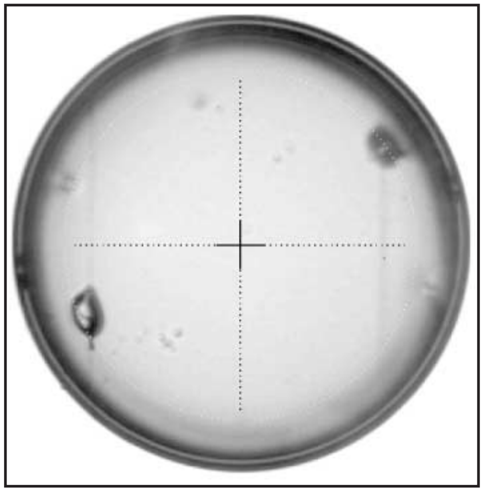
Despite the slow shock speed in the fiber, the average shock speed is greater than in a homogeneous mixture:

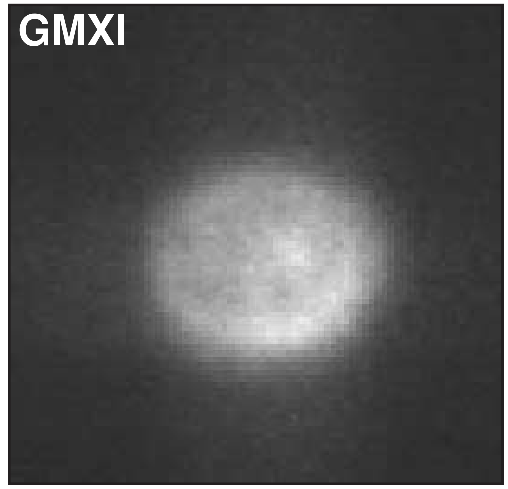




TC6315b

First OMEGA cryogenic wetted-foam target implosion demonstrated the highest cryogenic neutron yield



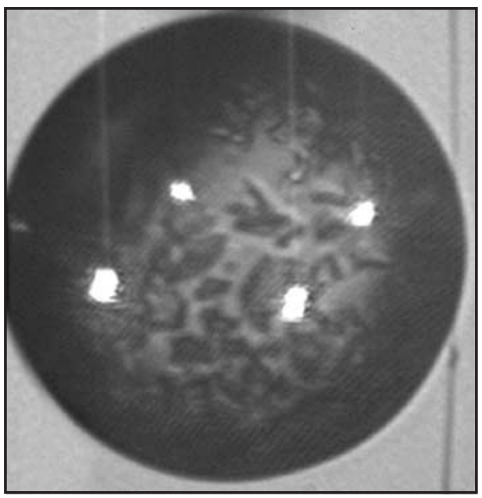


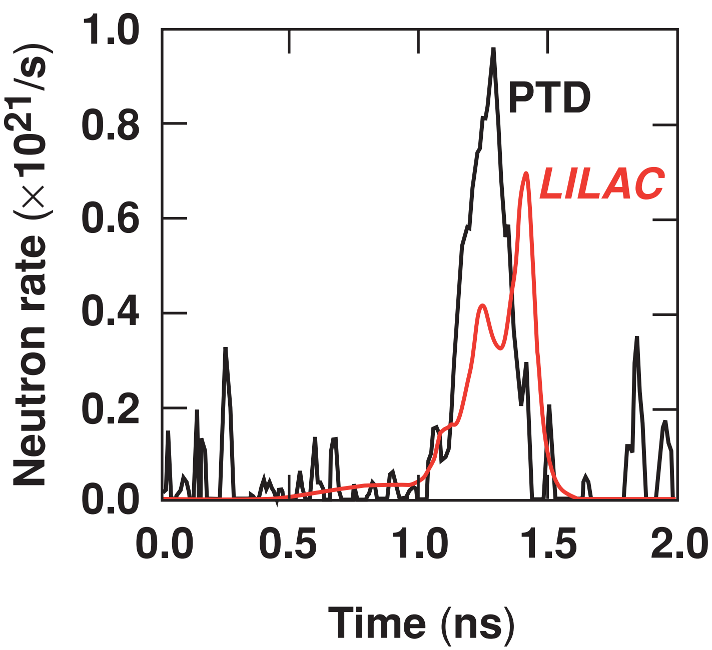
Experiment:

Y_{1n} = 1.74E11

Y_{2n} = 3.52E08

T_{ion} = 5.2 keV





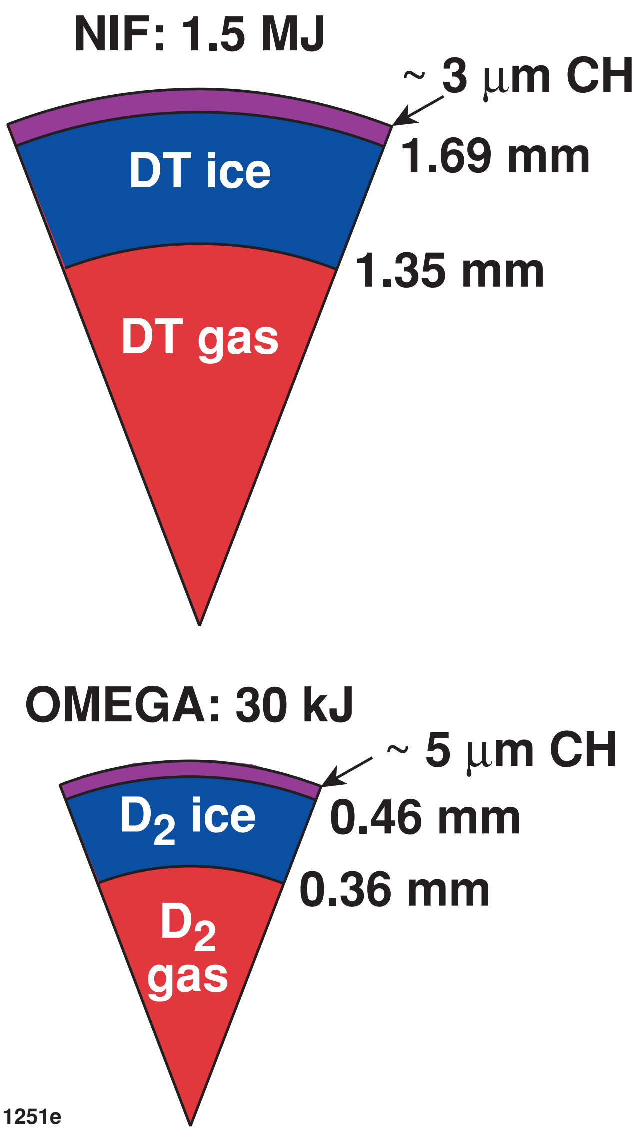
LILAC

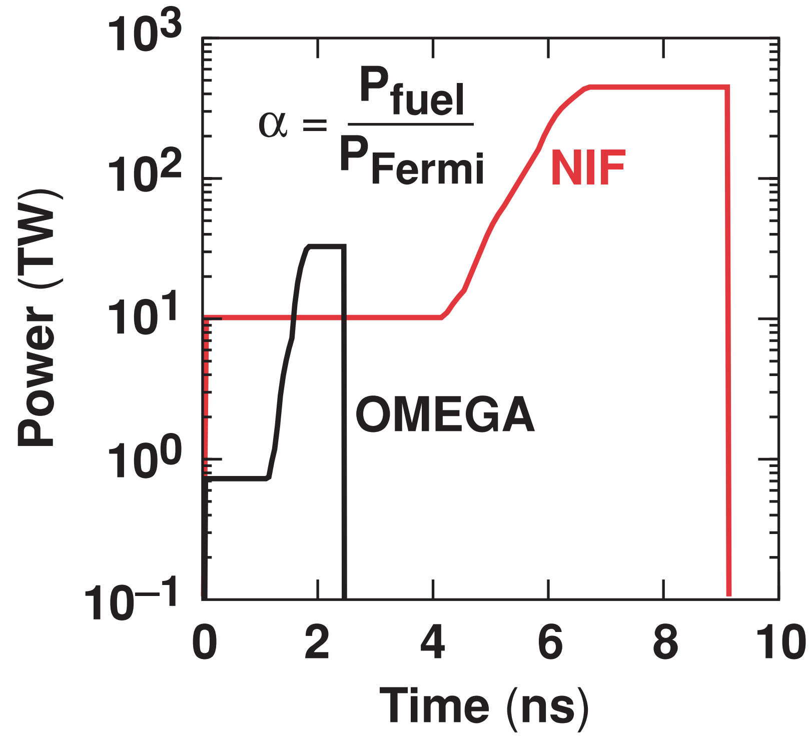
$Y_{1n} = 1.5^{3} \times 10^{11}$

$Y_{2n} = 1.18 \times 10^{9}$

T_{ion} = 2.7 keV

The second phase of the OMEGA cryogenic implosion campaign examines ignition-scaled targets at lower adiabats

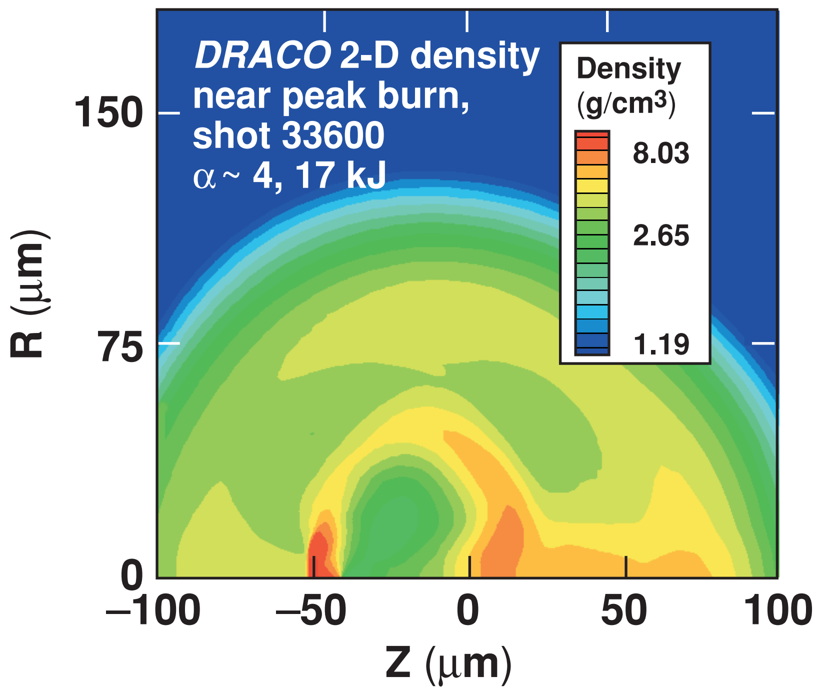


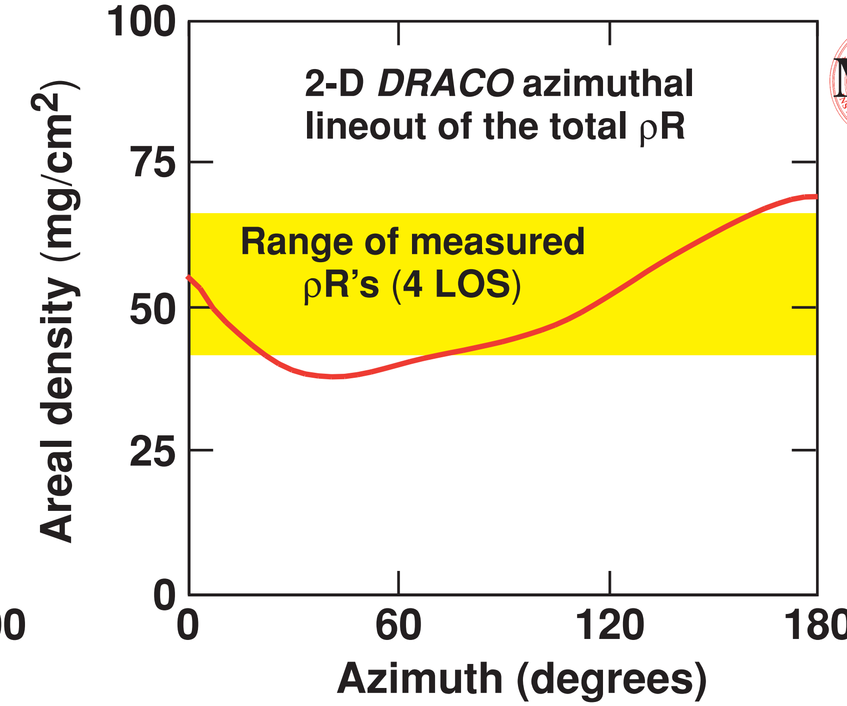


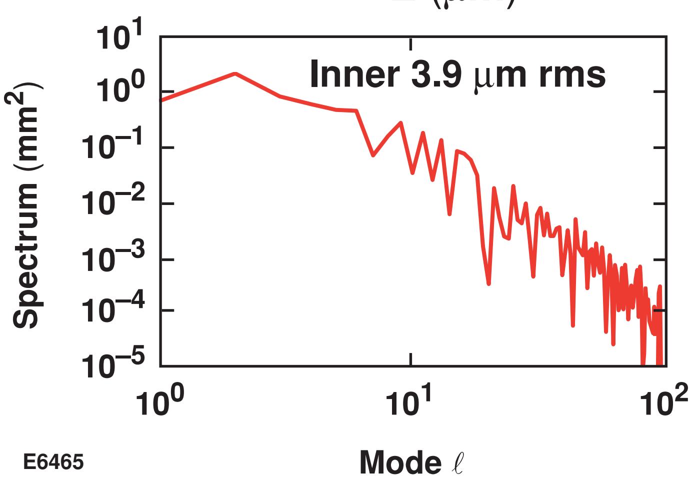
Energy ~ radius^3;
power ~ radius^2;
time ~ radius

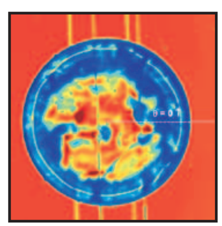
E11251e

2-D *DRACO* demonstrates good agreement in predicting target performance for shot 33600 ($\alpha \sim 4$)









$\alpha \sim 4$
16% YOC
33600

	Expt	1-D	2-D
Y_{1n}	4.30×10^9	2.68×10^{10}	5.85×10^9
Y_{2n}	4.43×10^7	1.40×10^9	5.97×10^7
<ρR>	52	63	55
T_{ion}	2.7	1.6	1.4

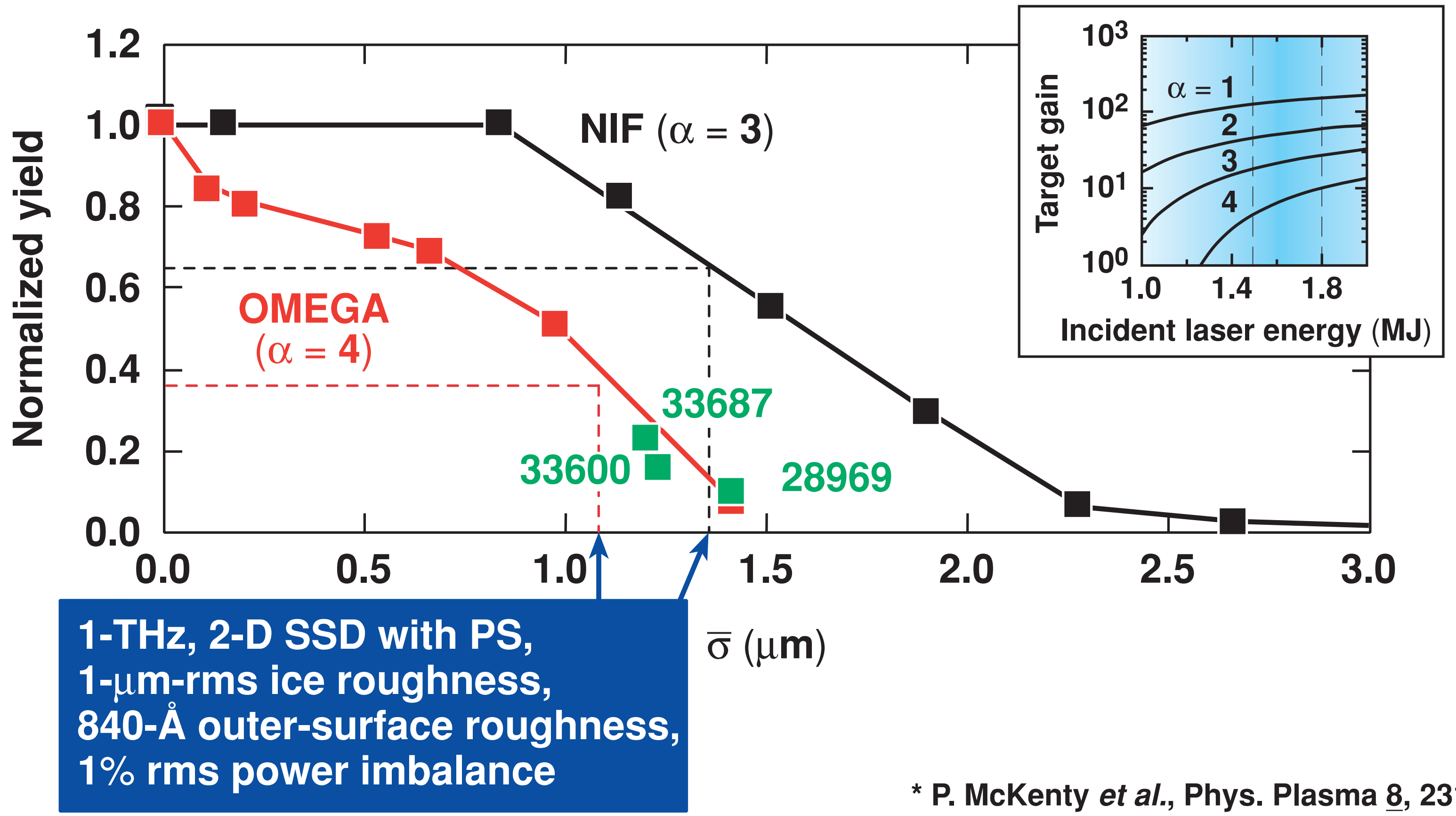
E6465

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

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

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

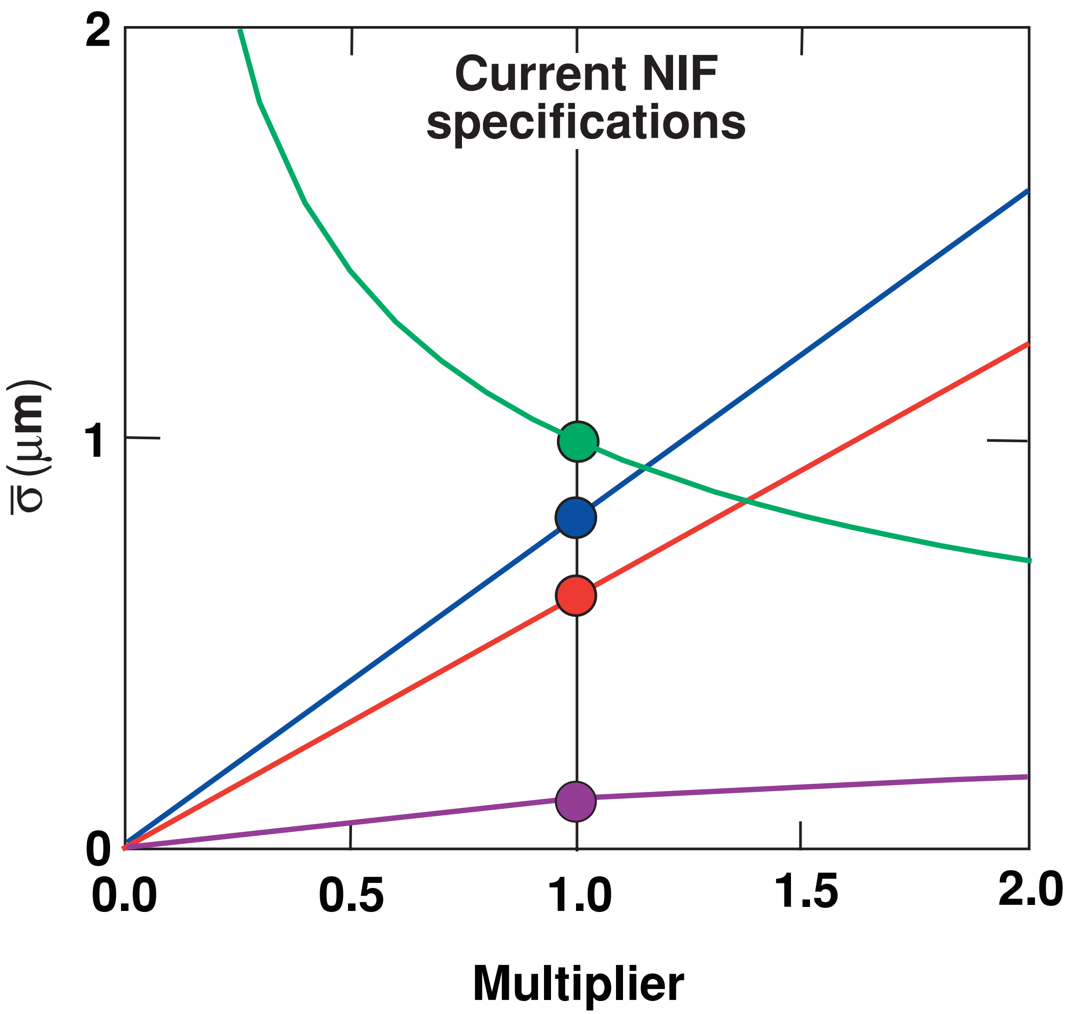
where the σ_ℓ's are the rms amplitudes at the end of the acceleration phase.

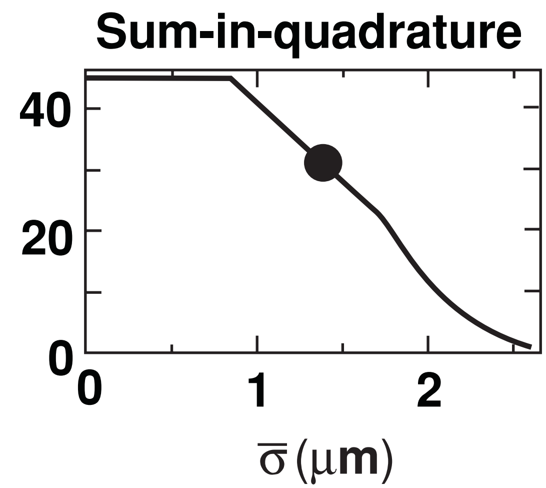


* P. McKenty *et al.*, Phys. Plasma 8, 2315 (2001).

E12008g

Scaling gain with $\bar{\sigma}$ allows the formation of a global nonuniformity budget for the direct-drive point design

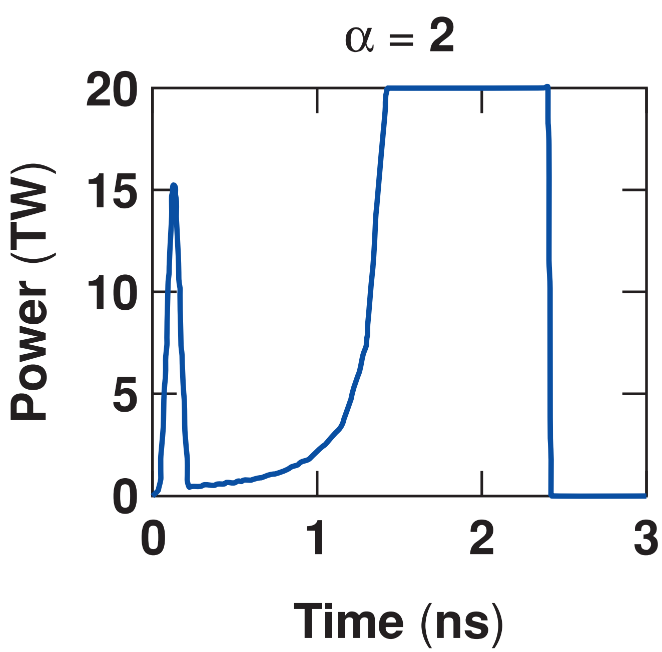




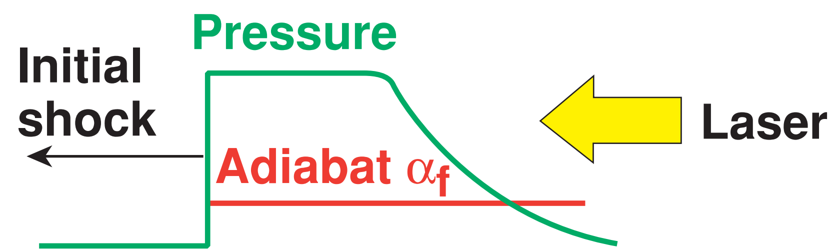
- Applied SSD bandwidth (2 color cycle × 1 THz)
- On-target power imbalance (× 2% rms)
- Inner-surface roughness (× 1-μm rms)
- Outer-surface roughness (× 80 nm)

TC5577a

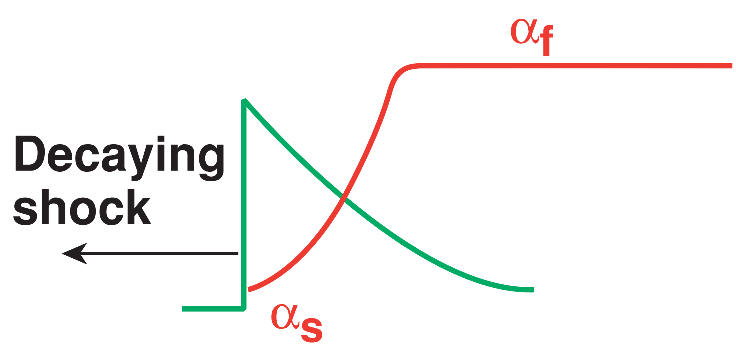
Adiabat shaping is achieved using a high intensity picket[1]



- $t = 0$ Picket creates a strong shock.
- $t = t_p$ Rarefaction wave (RW) is launched at $t = t_p$.



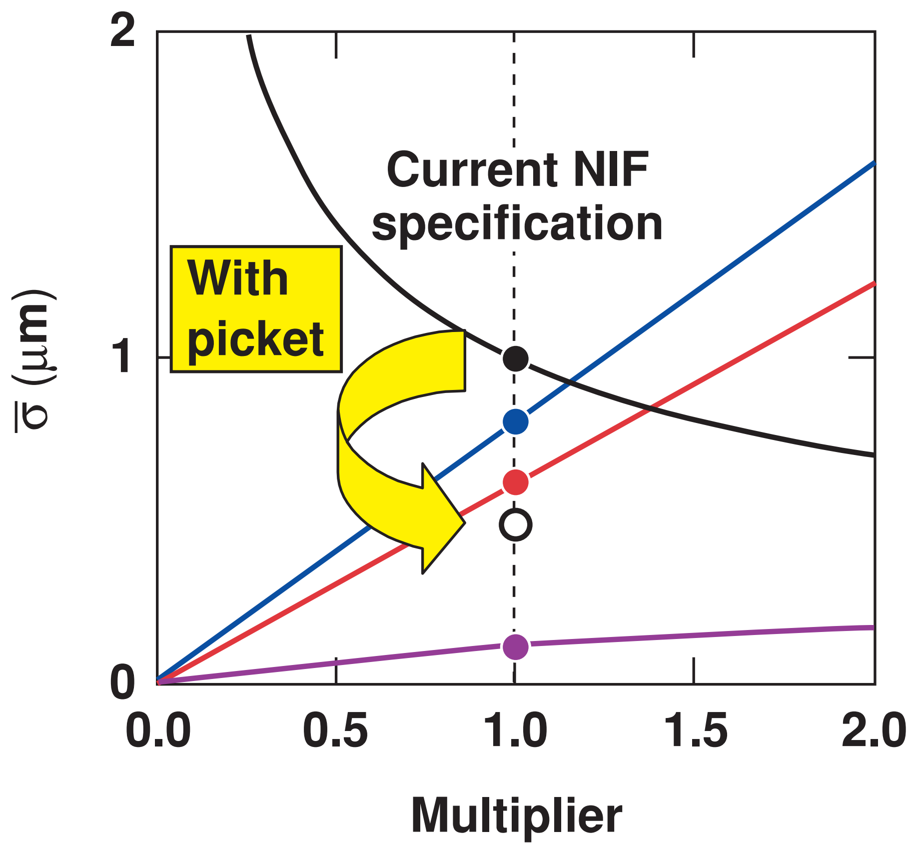
- $t = t_{RW}$ RW meets the shock.
- $t > t_{RW}$ Shock strength decreases in time.

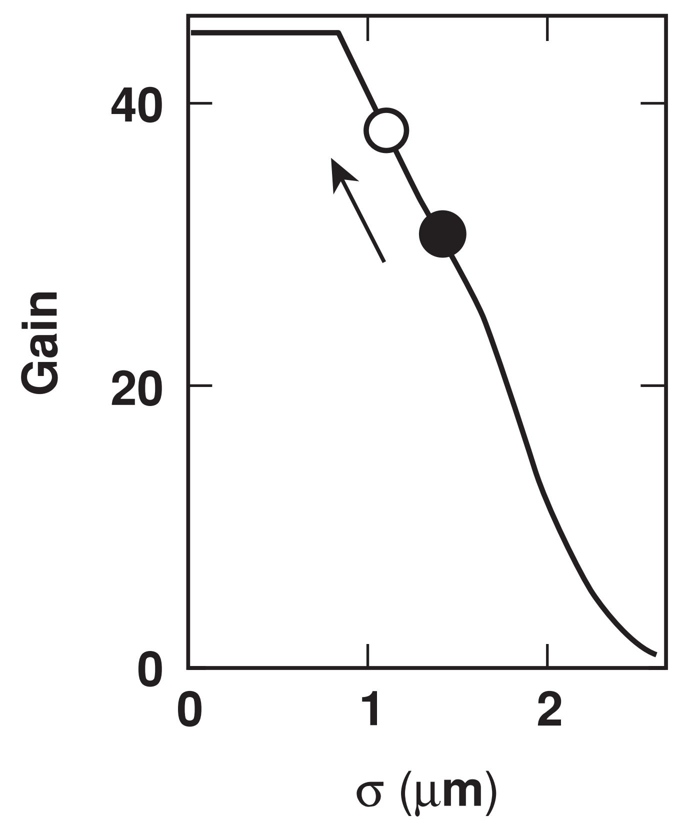


For DT foils:[2] $\gamma = 0.94\sqrt{kg} - 2.6\ kV_a$, where $V_a \sim \alpha^{3/5}$.

[1] V. N. Goncharov *et al.*, Phys. Plasmas 10, 1906 (2003).
[2] R. Betti *et al.*, Phys. Plasmas 5, 1446 (1998).

Direct-drive target stability is dramatically improved when adiabat shaping is applied

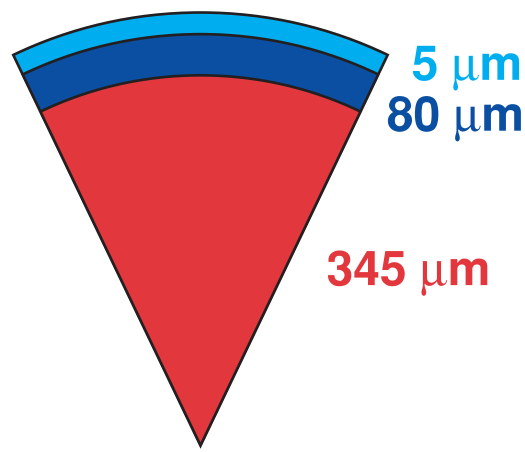


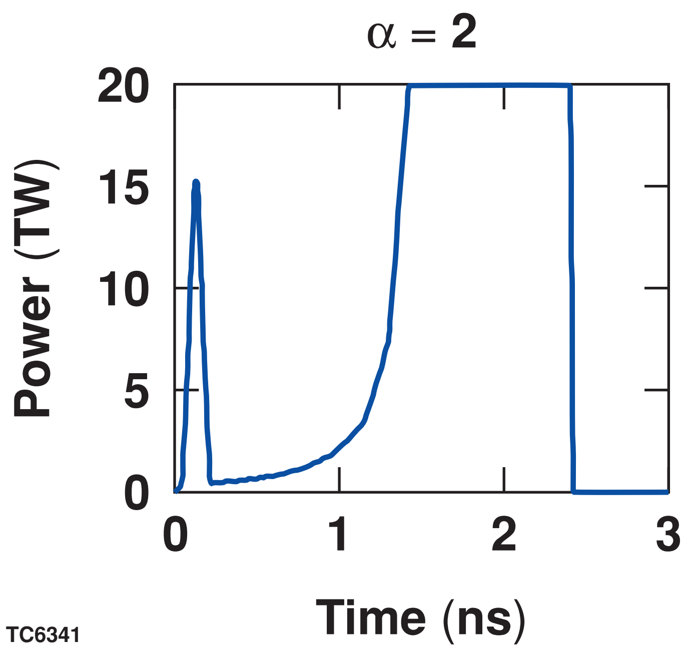


The benefit of pickets has been confirmed in NRL and LLNL simulations.

TC6339b

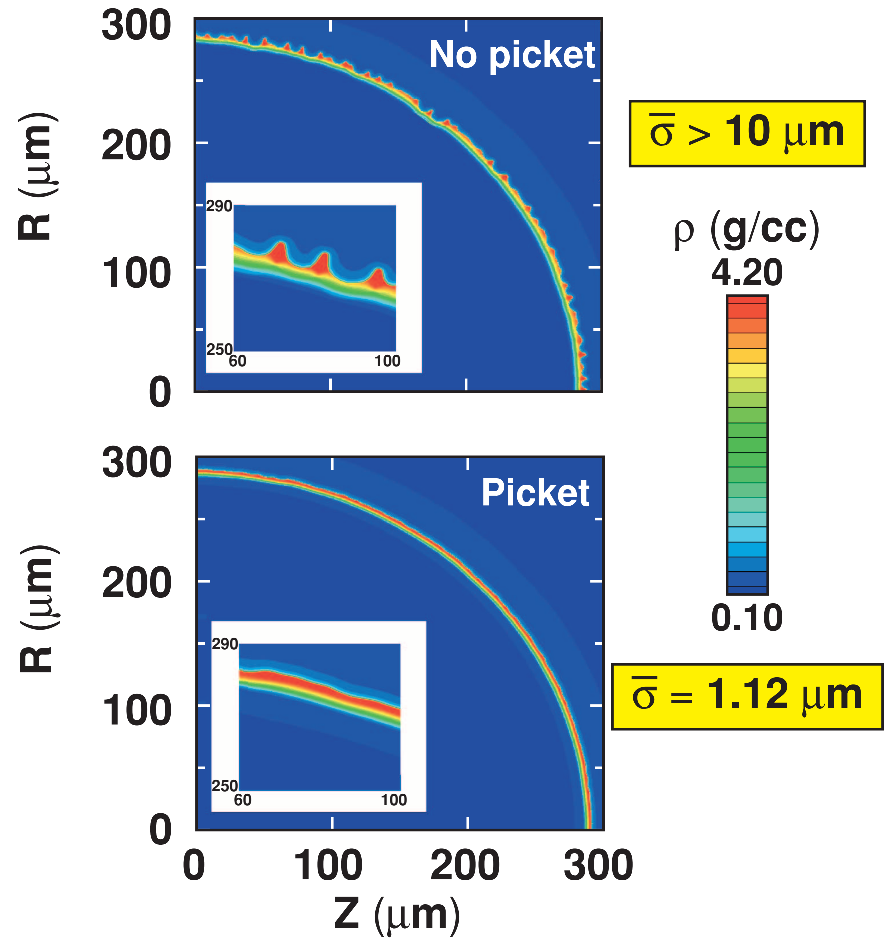
Picket results have led to lower-adiabat, OMEGA scaled-ignition designs





Imprint simulations

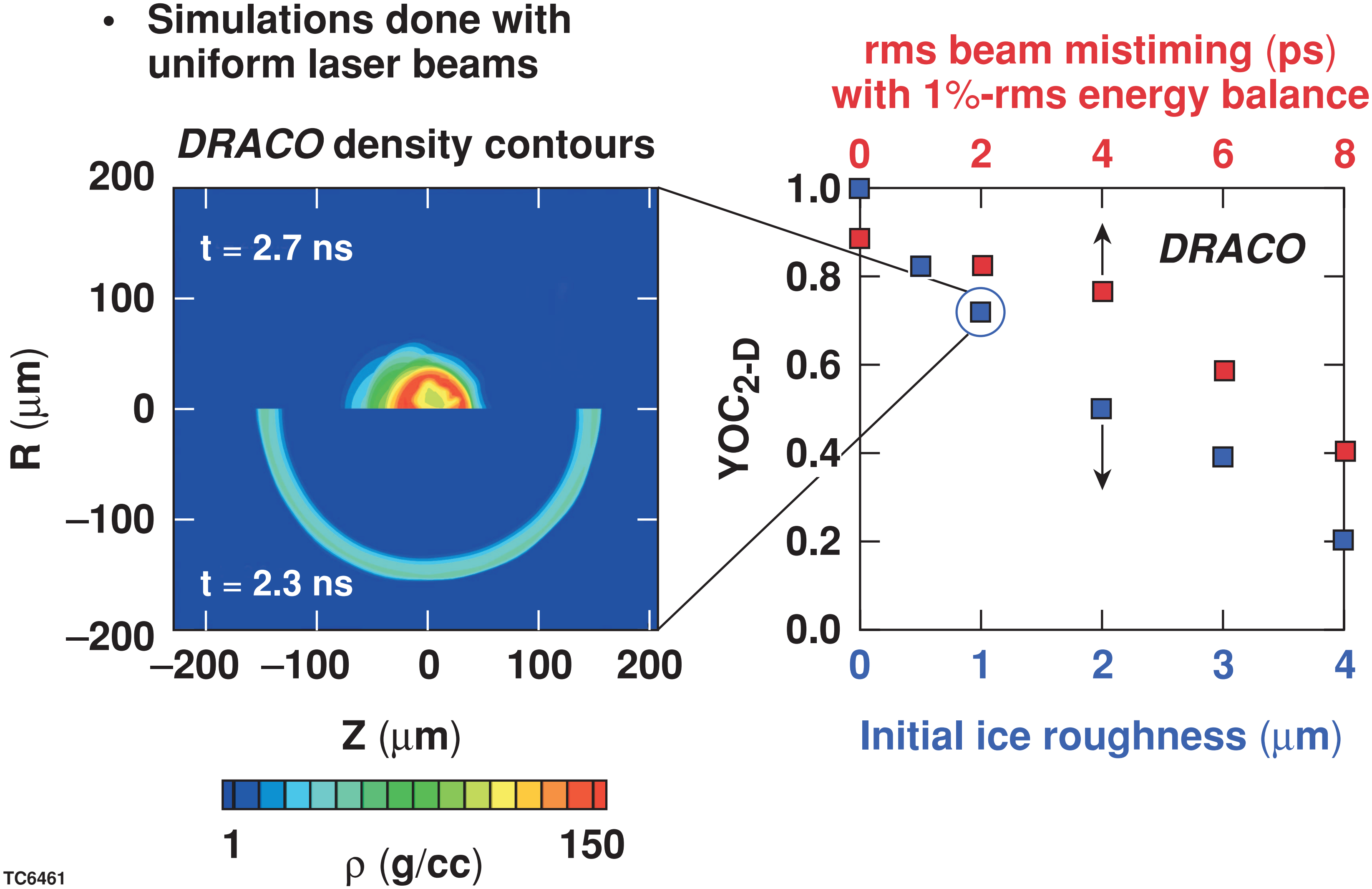
ORCHID: ℓ = 2–200, DPP + PS, 1-THz SSD



TC6341

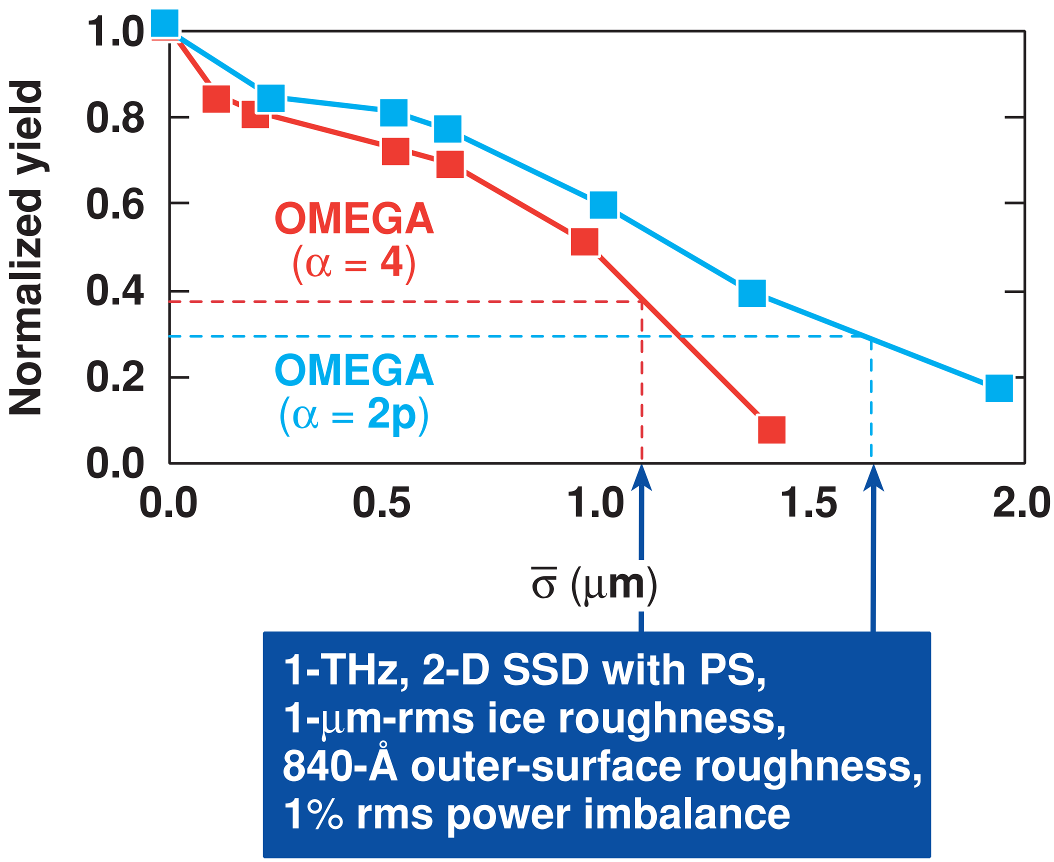
A series of 2-D *DRACO* runs are compiled to obtain $\bar{\sigma}$ scaling for the α = 2p design

- Simulations done with uniform laser beams



TC6461

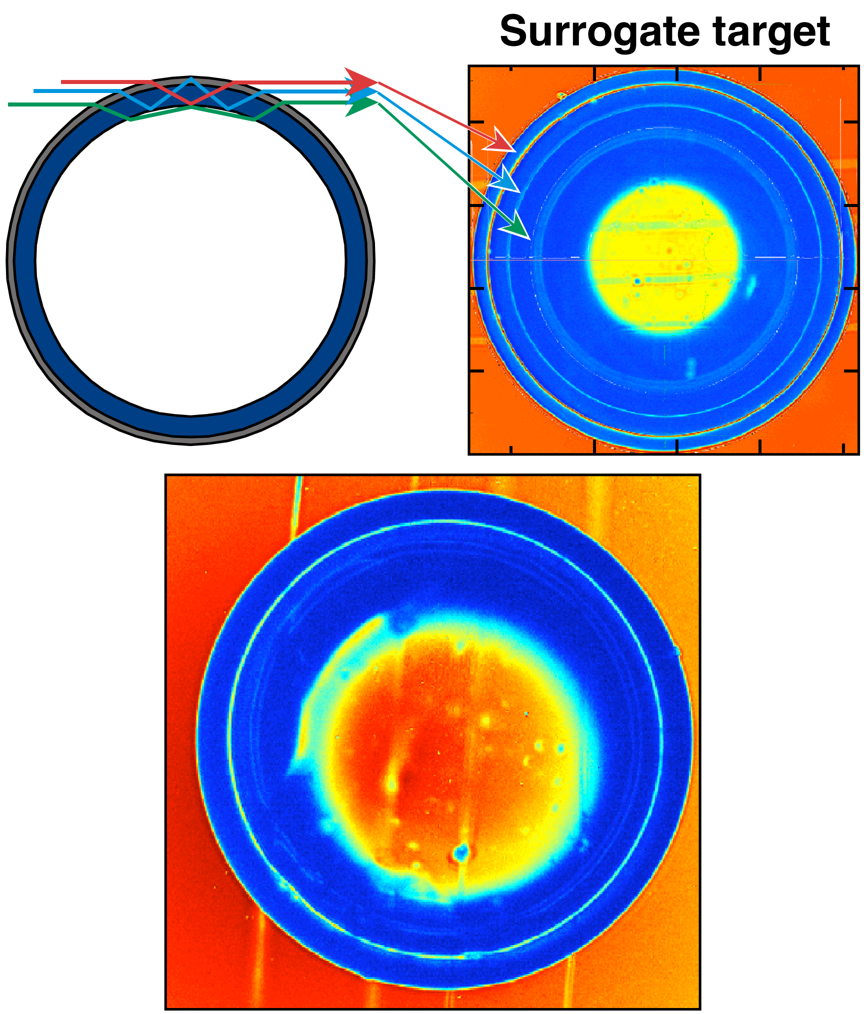
With the advent of adiabat shaping and improved ice-layer finishes, lower-adiabat implosions can now be fielded with confidence on OMEGA

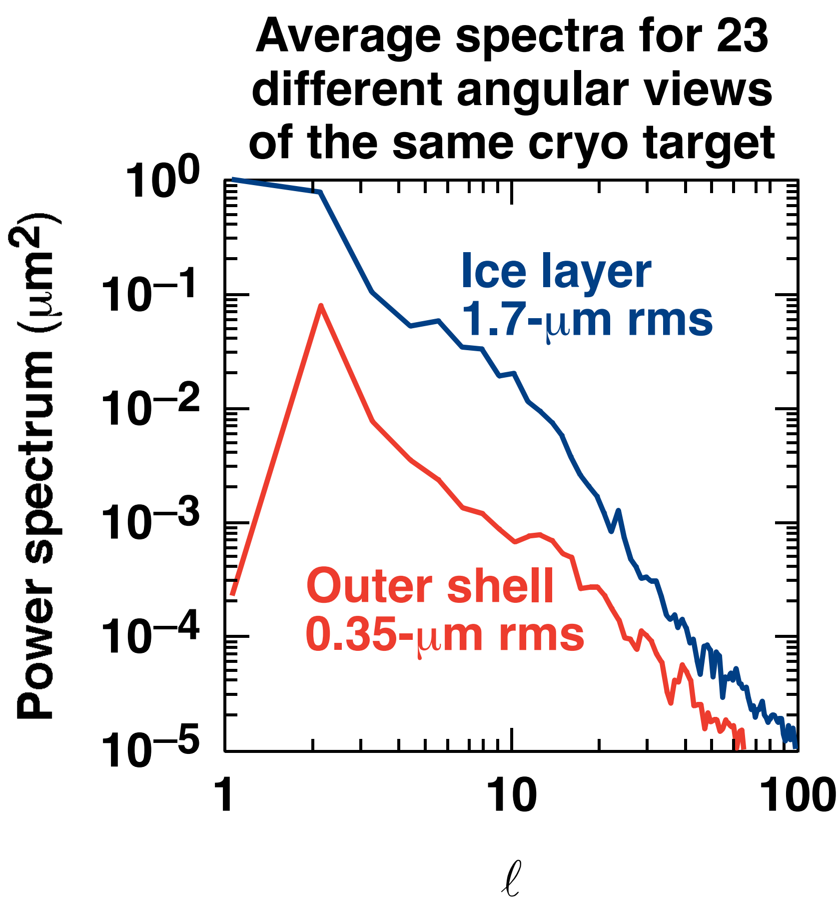


Addition of picket leads to similar stability and performance for lower-adiabat implosions.

E12484

Recent D_2-ice layers with IR heating are approaching the NIF 1-μm rms requirement





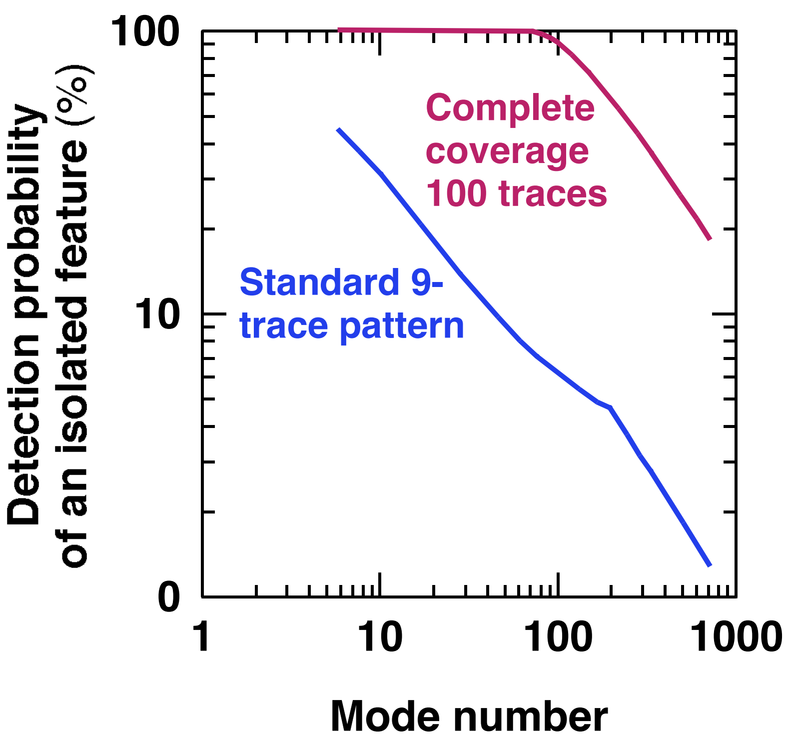
930-μm-diam OMEGA cryo target with 100-μm-D_2-ice layer and 3.5-μm-CH shell

E12272d

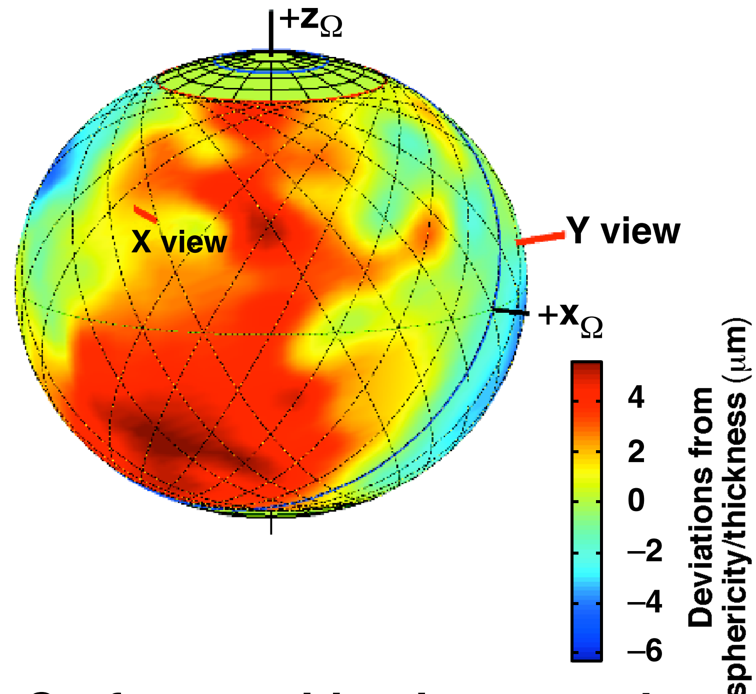
Accurate three-dimensional reconstructions for simulations require many sampling traces

UR LLE

GENERAL ATOMICS
(Courtesy of R. Stephens)



Topographical reconstruction



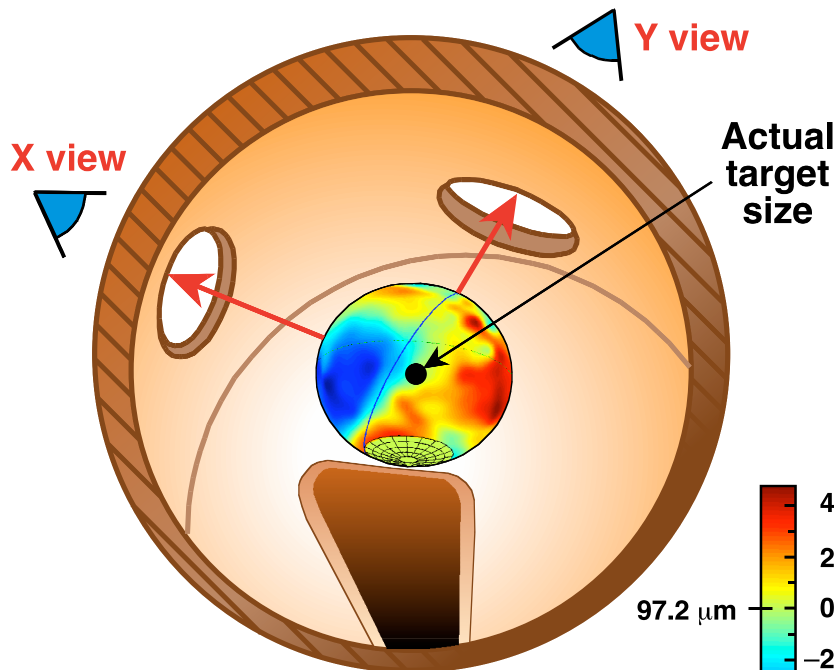
- Surface position is mapped onto sphere.
- Data are smoothed.
- Information for low-order modes is provided.

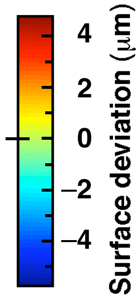
E12255b

Causes of ice roughness have been identified and are being addressed

(I) Illumination nonuniformity in the layering sphere due to the windows and target-removal port ("keyhole") causes asymmetric heating.

Experimental results

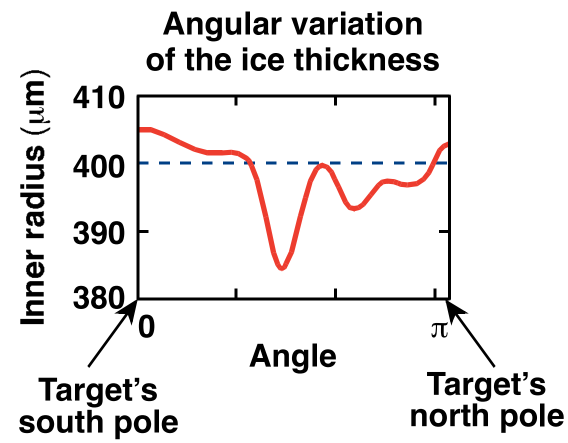


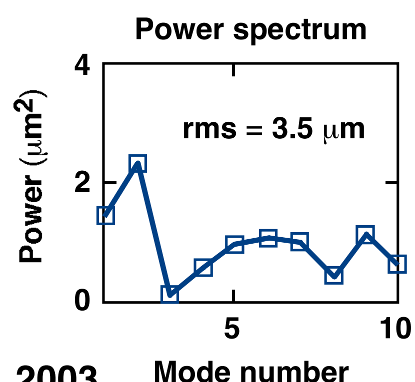


- Keyhole area is 2% of layering sphere.
- Refraction causes nonuniform heating that induces low-mode roughness.

Simulation results*

(circular keyhole)





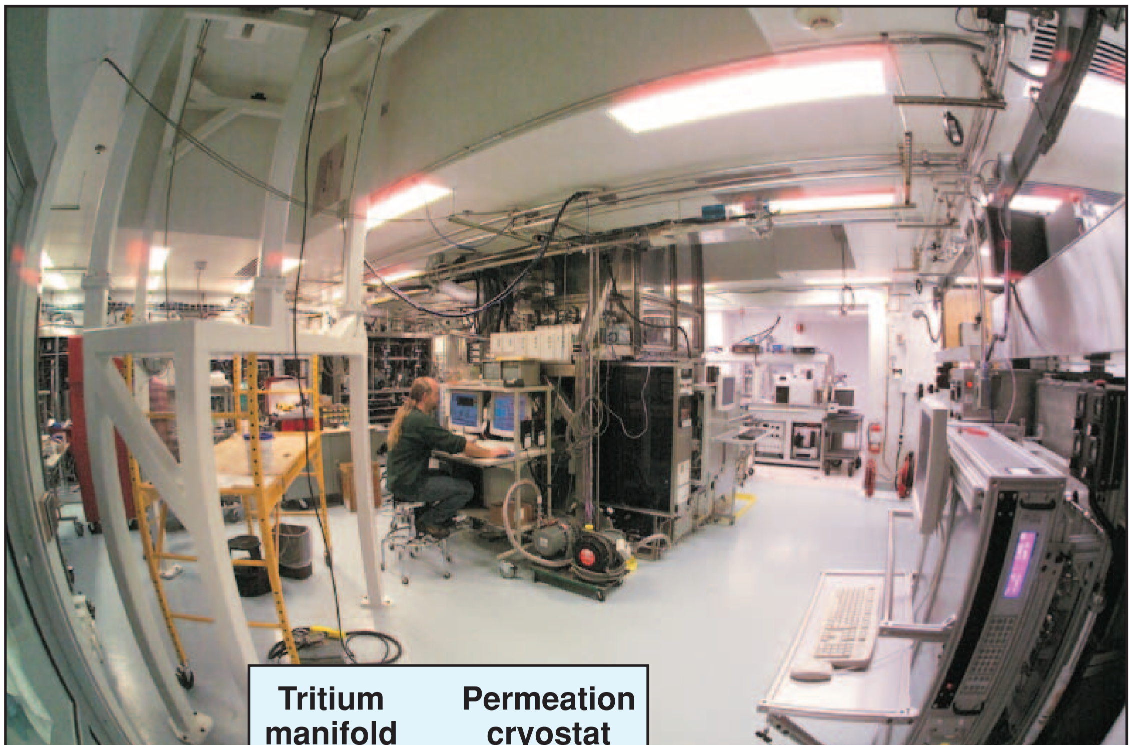
T1861b

* M. Wozniak, Summer High School Project Report, 2003

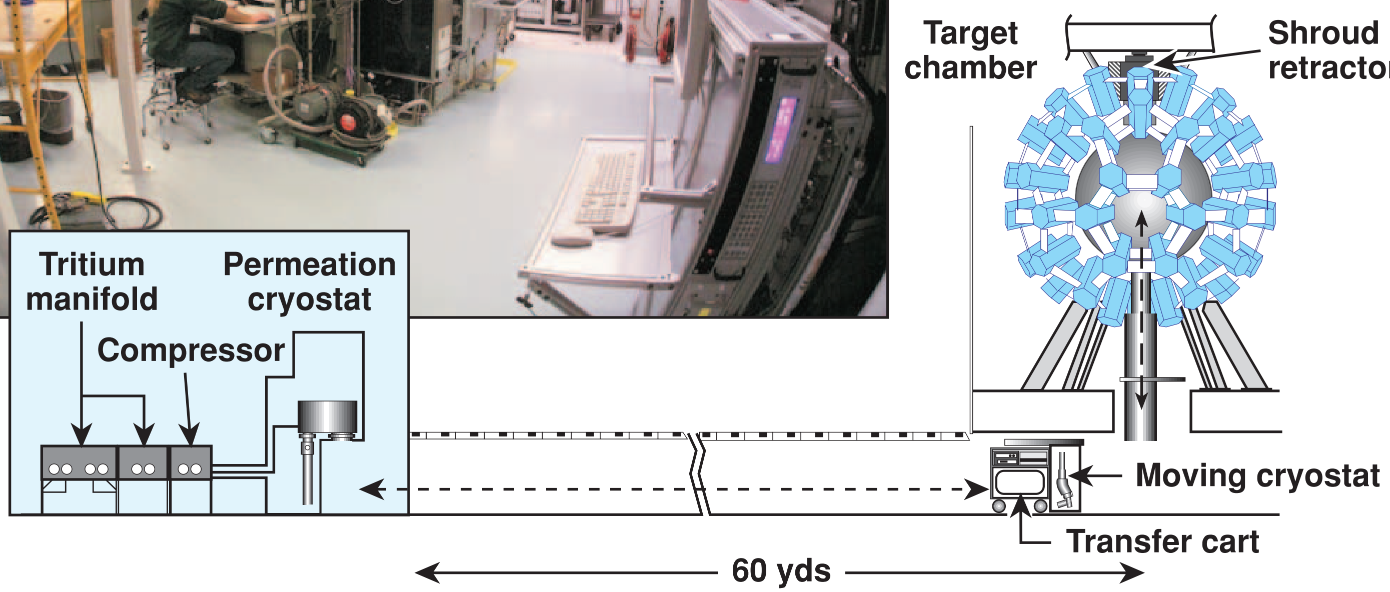
New D_2 Fill and Transfer Station (FTS) under construction will provide concurrent DT and D_2 cryogenic operations in late FY04

UR LLE

Cryogenic and tritium facility

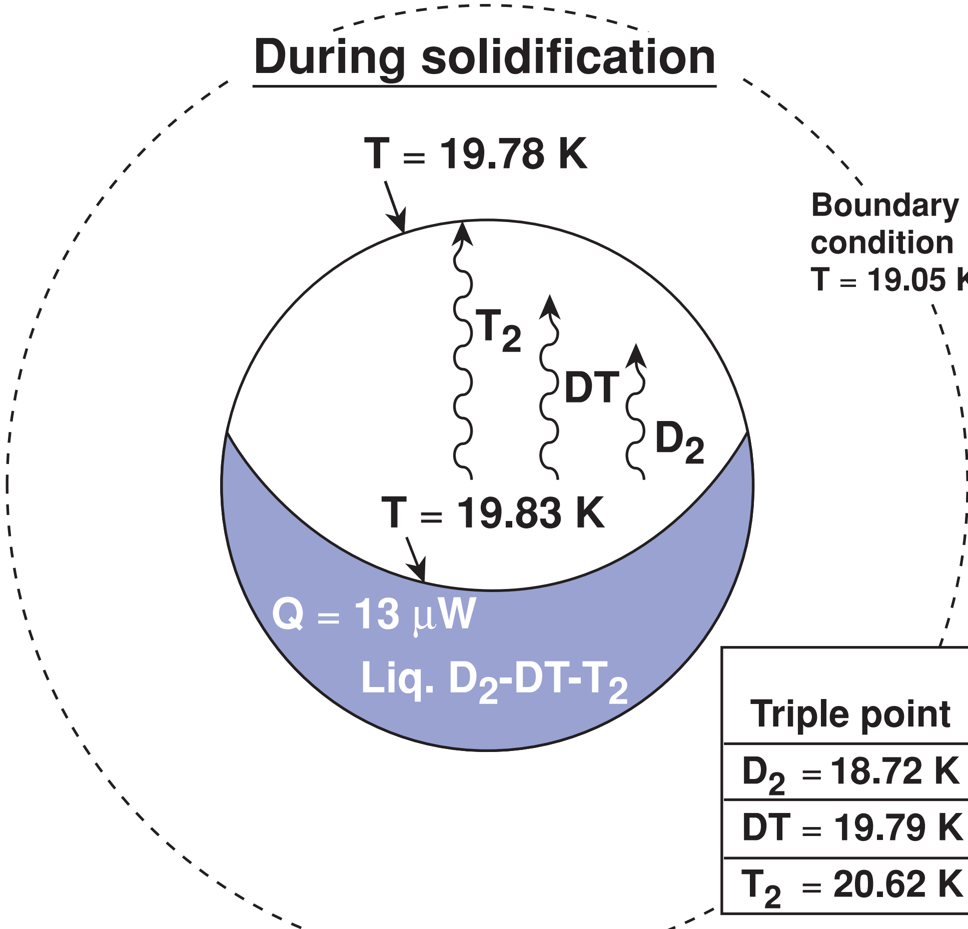


- Targets (4) are filled and characterized.
- Filling and cooling targets requires 66 h.
- Layering requires 24 h.

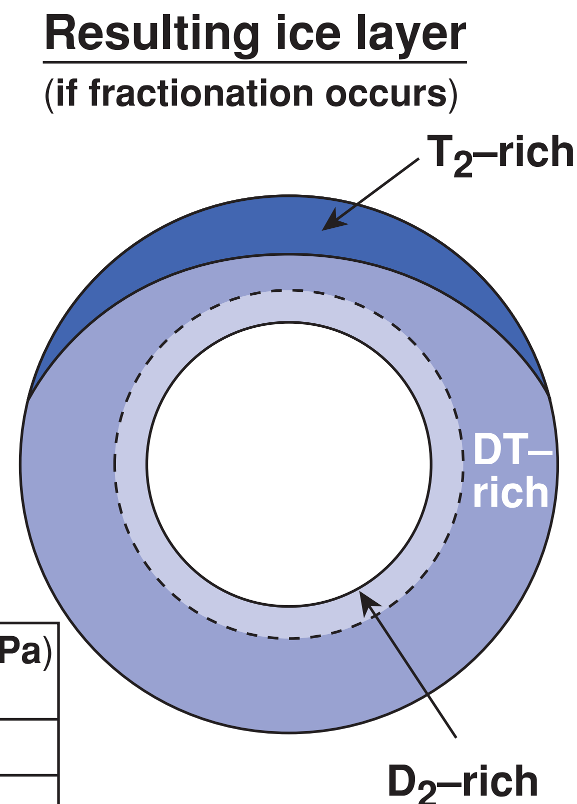


TC6459

Slow solidification produces the smoothest deuterium ice layers but increases the possibility of fractionation in D_2-DT-T_2 mixtures



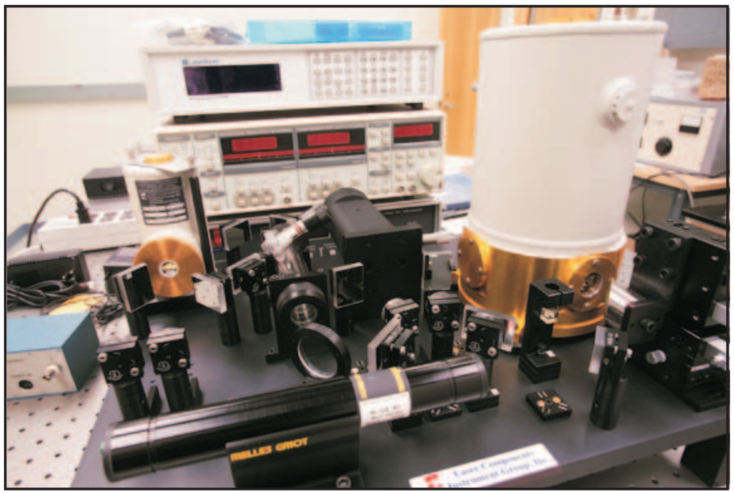
Triple point	Vap. press. (Pa) at 19.79 K
D_2 = 18.72 K	2930
DT = 19.79 K	2200
T_2 = 20.62 K	1580



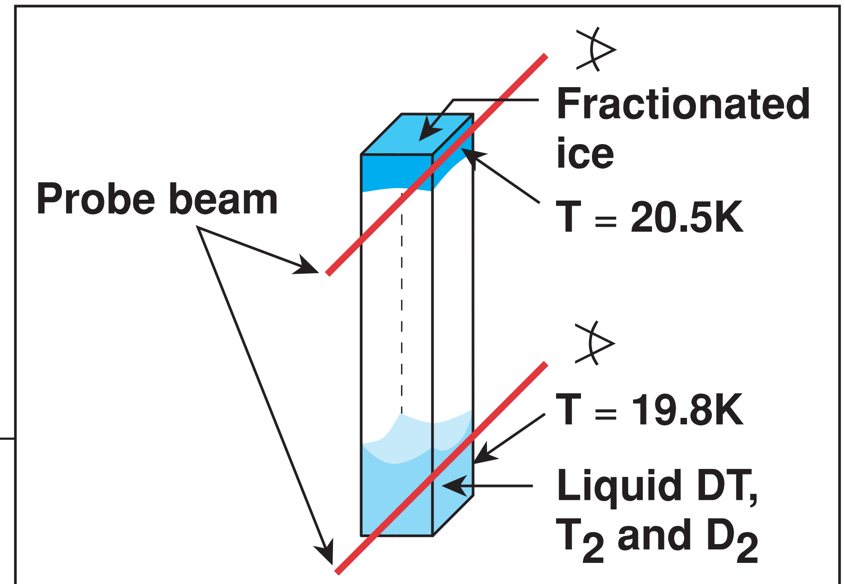
Diffusion coefficients for liquid hydrogen isotopes are high ~ 5×10^{-9} m^2/s at ~ 20 K, eliminating D_2-DT-T_2 concentration gradients in the liquid and allowing preferential T_2 redistribution.

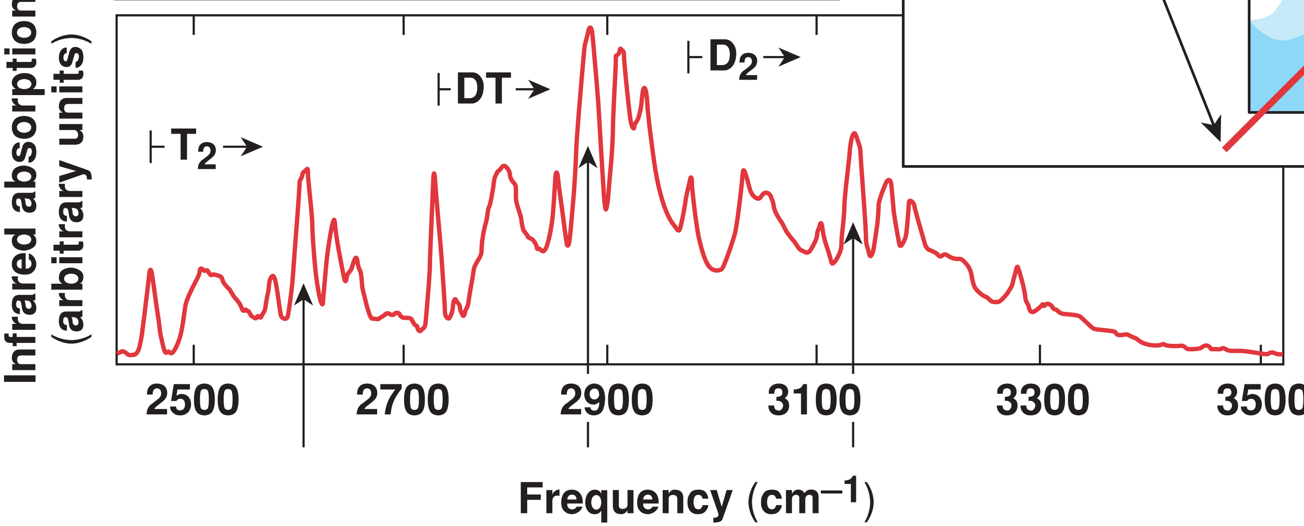
T1876

A spectroscopic probe using a laser diode will provide experimental confirmation of the existence or absence of D_2-DT-T_2 fractionation



Cryogenic transparent cell





T1877a

Summary/Conclusions

Recent improvements in critical areas of direct-drive uniformity have OMEGA beginning to demonstrate scaled-ignition performance of cryogenic implosions

UR LLE

- Adiabat-shaping techniques allow the fielding of lower-adiabat-implosion experiments on OMEGA.
- Extensive research and development have produced ice-layer finishes approaching the 1-μm NIF requirement.
- The cryogenic DT Fill and Transfer Station (FTS) is currently being qualified, and DT layering and fractionation studies will commence by the end of FY04.

For targets at TCC, 2-D *DRACO* simulations agree with experimental observations.