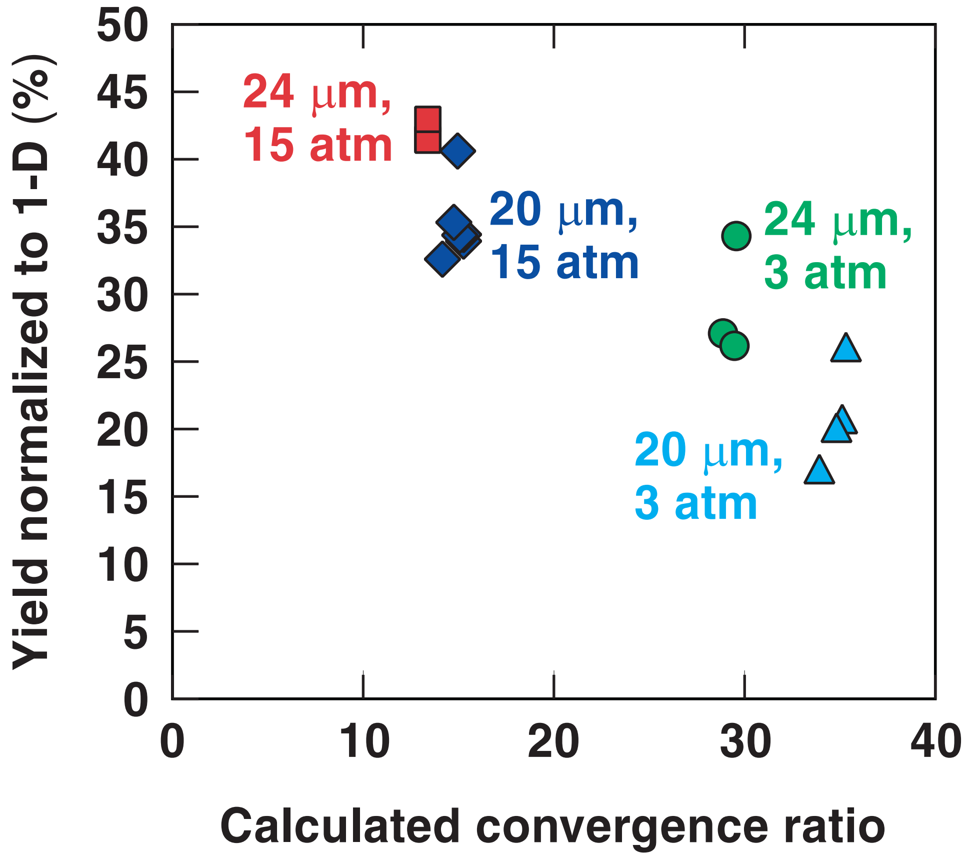
Core Density and Temperature Conditions and Fuel–Pusher Mix in Direct-Drive ICF Implosions



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42nd Annual Meeting of the
American Physical Society
Division of Plasma Physics
Québec City, Canada
23–27 October 2000

Core Density and Temperature Conditions and Fuel–Pusher Mix in Direct-Drive ICF Implosions

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The compressed cores of direct-drive capsule implosions on the OMEGA laser system are studied with a wide variety of nuclear, particle, and x-ray diagnostics. Simultaneous measurements constrain the inferred core temperature and density conditions and fuel–pusher mix. For example, secondary neutrons and protons are produced from primary tritons and ^{3}He's after differing amounts of slowing down; hence, their relative yields depend sensitively on the electron-temperature and fuel-density profiles. Plastic shells (typically CH) with wall thicknesses of 20 ~ 30 μm and diameters of ~920 μm are imploded with up to 30 kJ of laser energy with a variety of laser pulse shapes with durations ranging from 1 ~ 3 ns. The targets are filled with 3 to 15 atm of D_2, D ^{3}He, or DT to allow complementary nuclear and particle measurements. In some cases a small amount of Ar or Kr is added to the fuel to estimate the electron temperature and its profile. In addition, layers of CD or CHTi placed at or near the inner surface of the shell allow estimates of the fuel-pusher mix in various regions and of the electron temperature profile. This talk will describe the various measured quantities from directly driven implosions on OMEGA and the constraints they provide on simulations of the core profiles and fuel–pusher mix. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460.

*In collaboration with: J. A. Delettrez, R. Epstein, V. Yu. Glebov, R. L. Keck, R. L. McCrory, P. W. McKenty, F. J. Marshall, P. B. Radha, S. P. Regan, W. Seka, S. Skupsky, V. A. Smalyuk, J. M. Soures, C. Stoeckl, R. P. J. Town, and B. Yaakobi (LLE), R. D. Petrasso, J. A. Frenje, D. G. Hicks, F. H. Séguin, and C. K. Li (MIT), S. Haan, S. Hatchett, N. Izumi, R. Lerche, T. C. Sangster, and T. W. Phillips (LLNL)

Summary

Advances in individual-beam uniformity and power balance on OMEGA have greatly improved target performance

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- Individual-beam-uniformity improvements include 1-THz SSD and polarization smoothing (PS).
- For CR~15 targets (20 μm CH):
  - Fuel and shell areal densities are close to clean 1-D predictions.
  - Primary neutron yields are 35% of clean 1-D predictions.
  - Model shows small amounts of mix.
  - Single-beam nonuniformity is probably not the primary limitation on target performance.
- A wide variety of target types and fill pressures are utilized:
  - Provide self-consistency checks on diagnostic results;
  - Constrain core and fuel–shell mix profiles.
- The first 60-beam cryogenic implosions have been performed on OMEGA.

Collaborators

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Further details of this presentation can be found in various talks

- Most presentations will be Tuesday p. m. in session HO2.
- HO2.001: "Monochromatic Imaging of Direct-Drive Implosions on OMEGA" (F. J. Marshall)
- HO2.002: "Comparison of Neutron Burn History Measurements with One-and Two-Dimensional Hydrodynamic Simulations" (C. Stoeckl)
- HO2.003: "Time-Resolved Measurements of Compressed Shell Temperature and Areal Density with Titanium-Doped Targets on OMEGA" (V. A. Smalyuk)
- HO2.004: "A Measurement-Based Picture of Core Conditions in OMEGA Implosions" (P. B. Radha)
- HO1.006: "Charged-Particle Acceleration and Energy Loss Measurements on OMEGA" (D. G. Hicks)
- HO1.008: "Measurements of Areal Densities and Temperatures from DT Capsule Implosions on OMEGA" (C. K. Li; presented at end of session HO2, Tues. p.m.)
- HO1.007: "Secondary-Proton Spectra from D_2-Filled OMEGA Targets" (F. H. Séguin; presented at the end of session UO2, Thurs. a.m.)
- VO1.001: "Beam Power Matching on the OMEGA Laser" (R. L. Keck)
- GP1.080: "Measurement of Secondary Neutron Yield by Copper Activation" (V. Yu. Glebov)

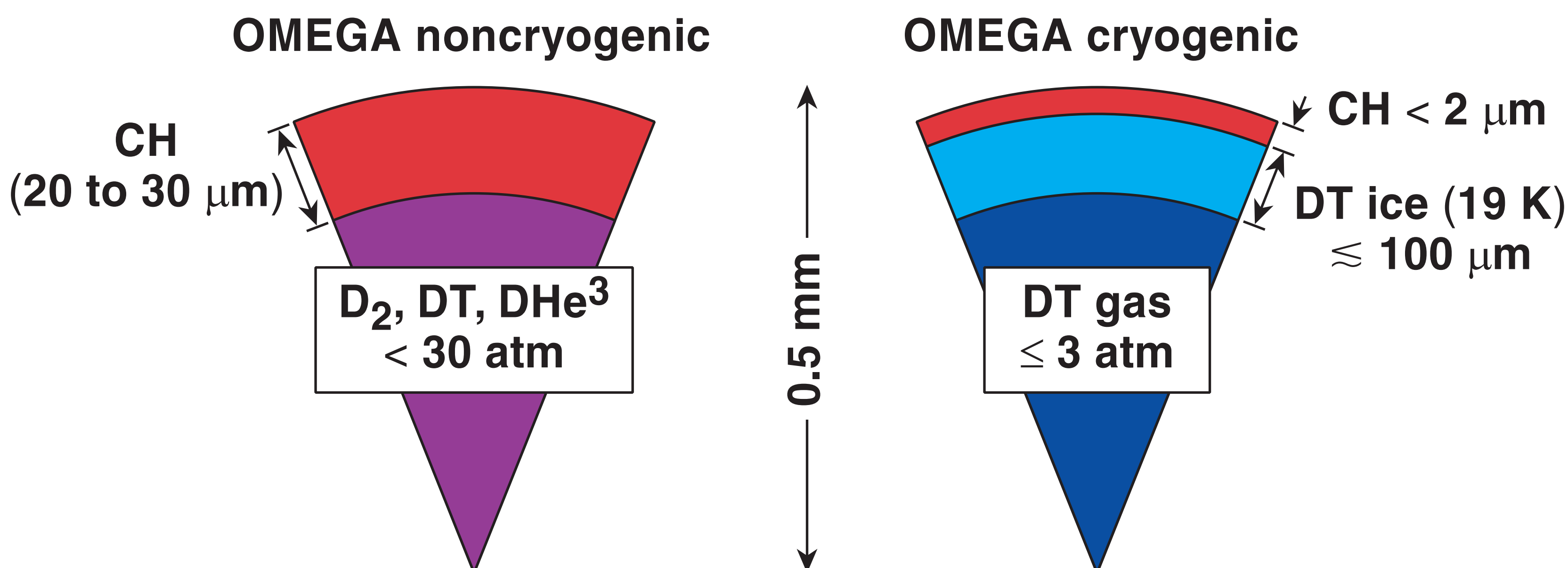
E10658

Outline

- Plastic-shell implosions
- OMEGA laser system and beam smoothing
- Target performance
- Mix-model results
- 60-beam cryogenic target shots
- Conclusions

Gas-filled-plastic-shell implosions are surrogates for cryogenic targets on OMEGA and NIF

- High-performance spherical implosions require that the shell (pusher) remain integral through the acceleration phase.
- 20- to ~24-μm-thick plastic shells imploded with 1-ns square pulses have shell stability properties similar to those of cryogenic targets on OMEGA.
- Plastic shells allow a wide variety of diagnostics of core conditions and fuel–shell mix.



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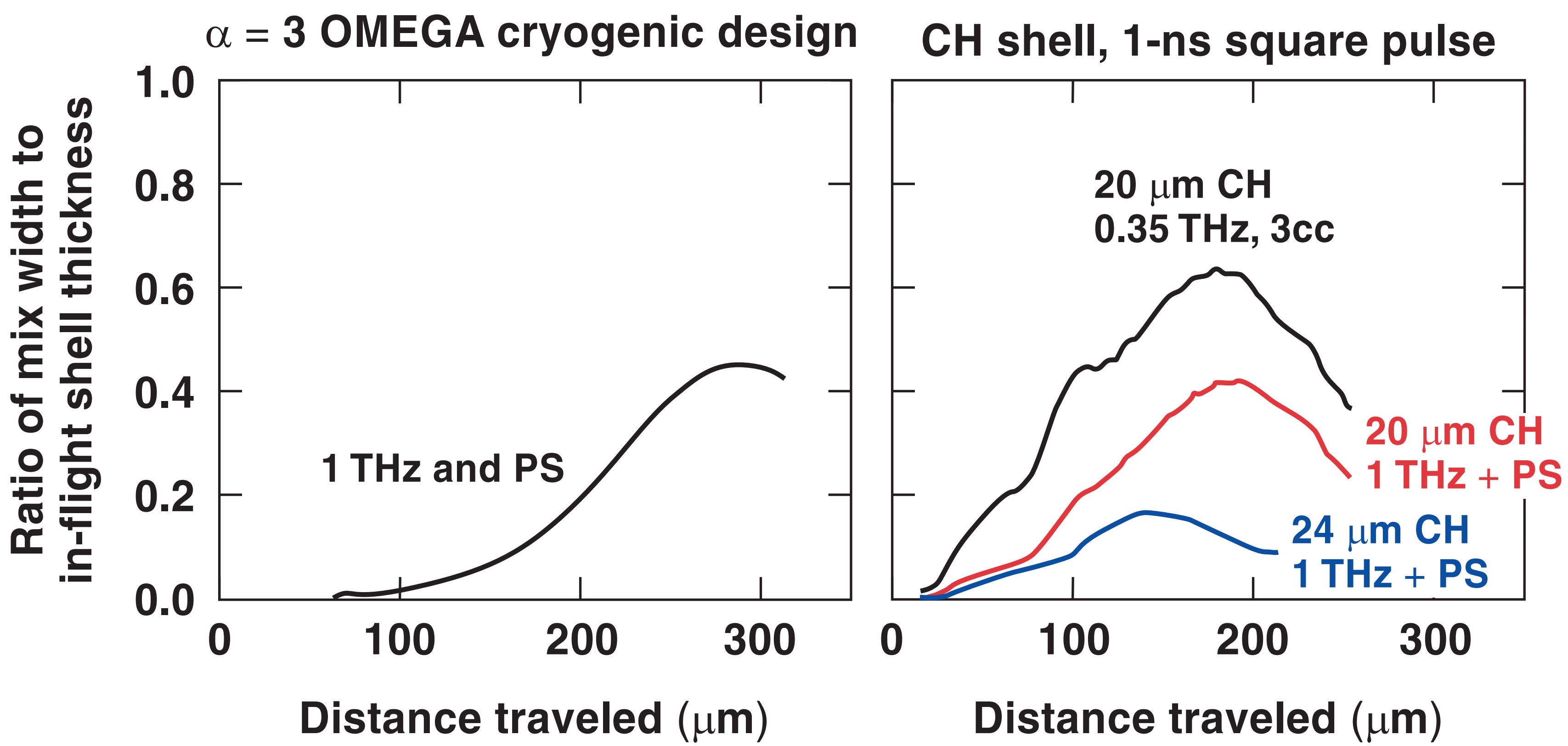
20-μm-thick plastic shells driven by 1-ns square pulses show similar shell stability to the OMEGA α = 3 cryo design

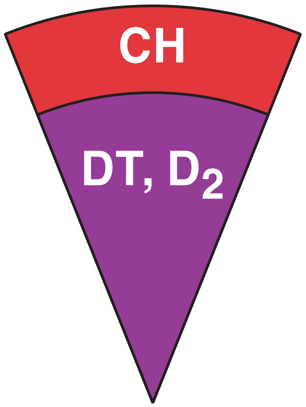


- Calculations are based on postprocessor* that includes effects of mass ablation, finite shell thickness, time variation in the unperturbed state, and spherical convergence.

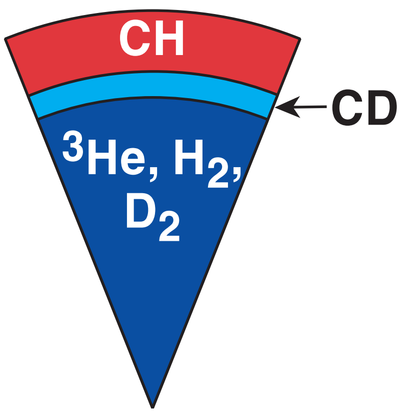
*Goncharov *et al.*, Phys. Plasmas; accepted for publicaton

E10705

A wide variety of target types and fill gases are utilized to infer core conditions and fuel–shell mix



Primary neutrons	yield, T_{ion}, burn history
Secondary neutrons	ρR_f
Secondary protons	ρR_f, ρR_{sh}
Knock-on D & T	ρR_f, ρR_{sh}
Knock-on p	ρR_{sh}
X-ray emission	R_f, T_e, shell integrity



- Inner and offset CD or CHTi layers allow measurements of inner-shell condition and fuel–shell mix.
- Tritons, protons, or x rays from the core probe the inner shell layer.
- Ar and Kr dopants in the fuel allow the temperature and density to be inferred.

A model of the core conditions and mix must be consistent with results from all target types.

E10662

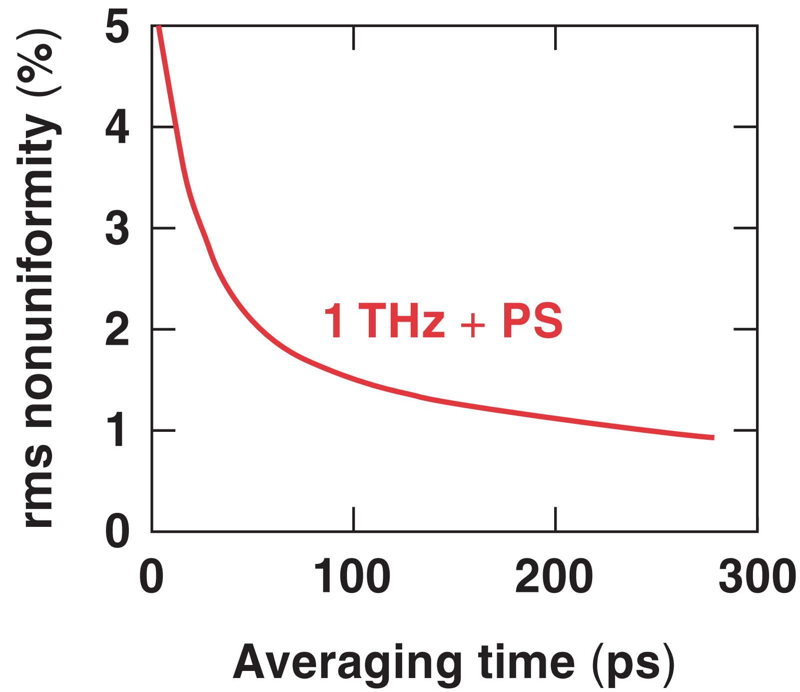
A wide variety of diagnostics is applied to spherical implosions

Primary yield	Cu, In activation, scintillator PMT's
Secondary neutron yield (GP1.080)	Scintillator PMT's, MEDUSA, Cu activation
T_{ion}	Scintillator PMT's
Neutron burn history (HO2.002)	Neutron temporal detector, bang-time detector
Charged particles (HO1.007, 008)	Charged-particle spectrometer (CPS), range filters
X-ray imaging (HO2.001, 003)	12× and 25× framing camera, KB microscopes
X-ray spectroscopy	Streaked and integrated crystal spectrometers

E10663

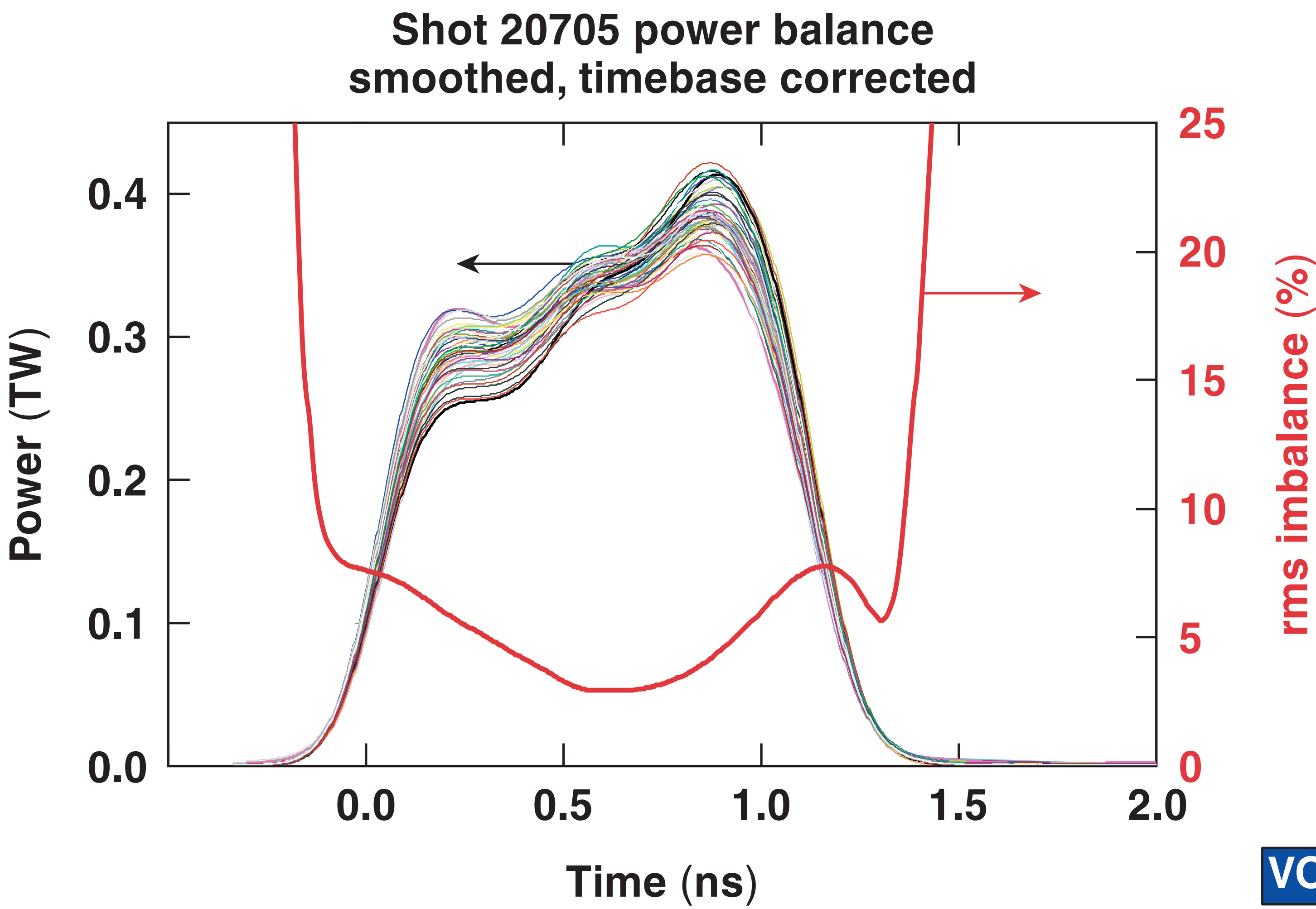
On-target beam uniformity on the 60-beam OMEGA laser system has been significantly improved

- Individual beam uniformity on 60 beams
  - Broad bandwidth, dual triplers
  - 1-THz SSD
  - Polarization smoothing (PS) utilizing birefringent wedges
  - High scattering and damaged optics have been replaced.
- Energy balance below 5% beam-to-beam rms (< 2% on target) is routinely achieved.



Beam-to-beam rms power imbalance is routinely 5% or less for square laser pulses

23 kJ, 1-ns square pulse, 50-beam plot



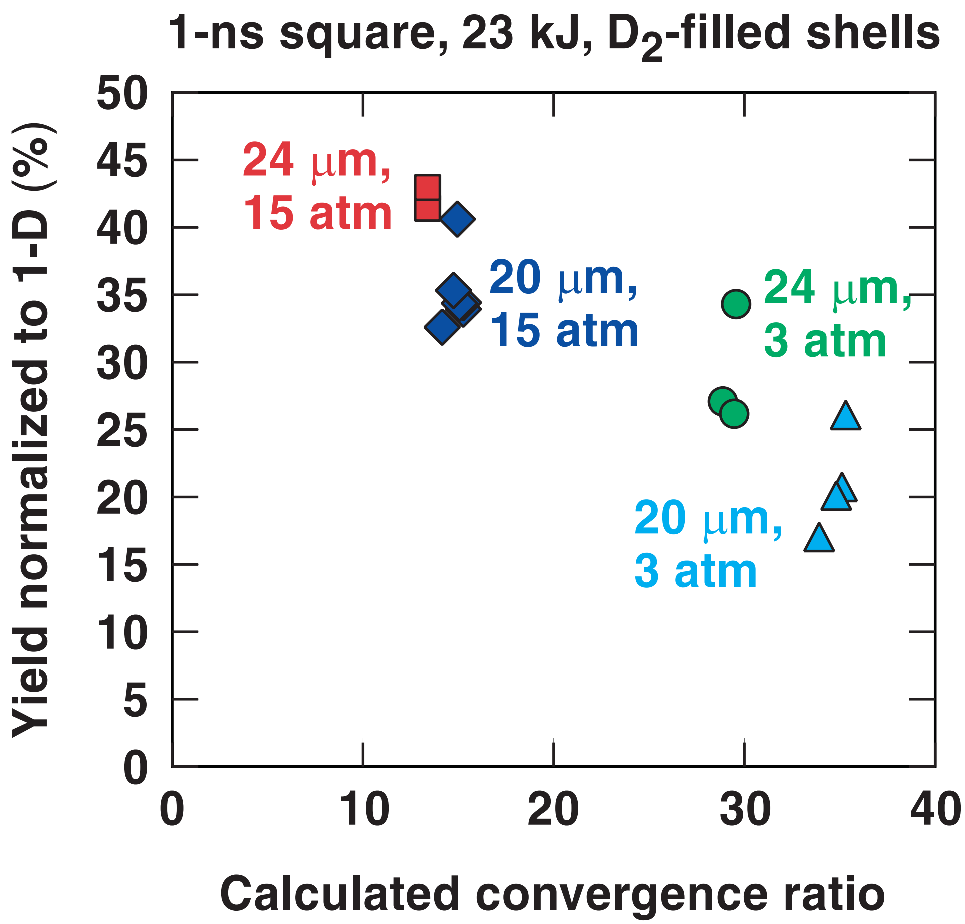
E10665

VO1.001

A large number of diagnostics are applied to a single target configuration

- Laser conditions
  - laser energy ~23 kJ
  - single color cycle, 1-THz SSD and polarization smoothing (PS)
    - some shots with 3-color-cycle SSD, 0.35 THz (no PS)
  - 1-ns square pulse shape
  - $<$ 5% rms beam-to-beam energy balance
- Targets
  - 3 to ~15 atm fill
  - 18 to ~20 to ~24 μm thick walls
  - 910 to ~930-μm-diameter
- The base-line 20-μm-thick target with 15 atm fill has a calculated convergence ratio of 15.

Plastic-shell implosions with 1-THz SSD and PS show good reproducibility and performance

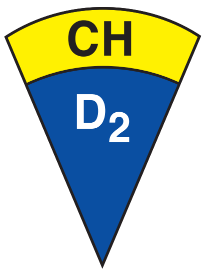


- These results suggest that single-beam nonuniformity is no longer the primary limitation of target performance.

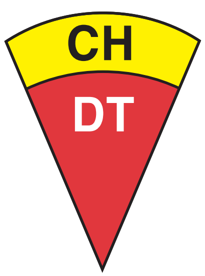
E10668

Target performance improved significantly with 1-THz SSD and polarization smoothing (PS)

19-μm-thick CH shells with 15 atm of D_2 or DT fill; C_R ~ 15; 1-ns square pulse, 23 kJ



Diagnostic	0.35-THz SSD	1-THz SSD & PS
D_2 primary yield (10^{10})	9±1	16±1
T_{ion} (D_2)	3.2 keV	3.7 keV
Sec. neutron ratio ($Y_{2n}/Y_n 10^{-3}$)	1.5±0.4	2.5±0.2
Sec. proton ratio ($Y_{2p}/Y_n 10^{-3}$)	1.4±0.2	1.9±0.2



DT primary yield (10^{12})	6±1	11±1
T_{ion} (DT)	3.7 keV	4.4 keV
Knock-on fuel ρR (mg/cm^2)	9±2	15±2

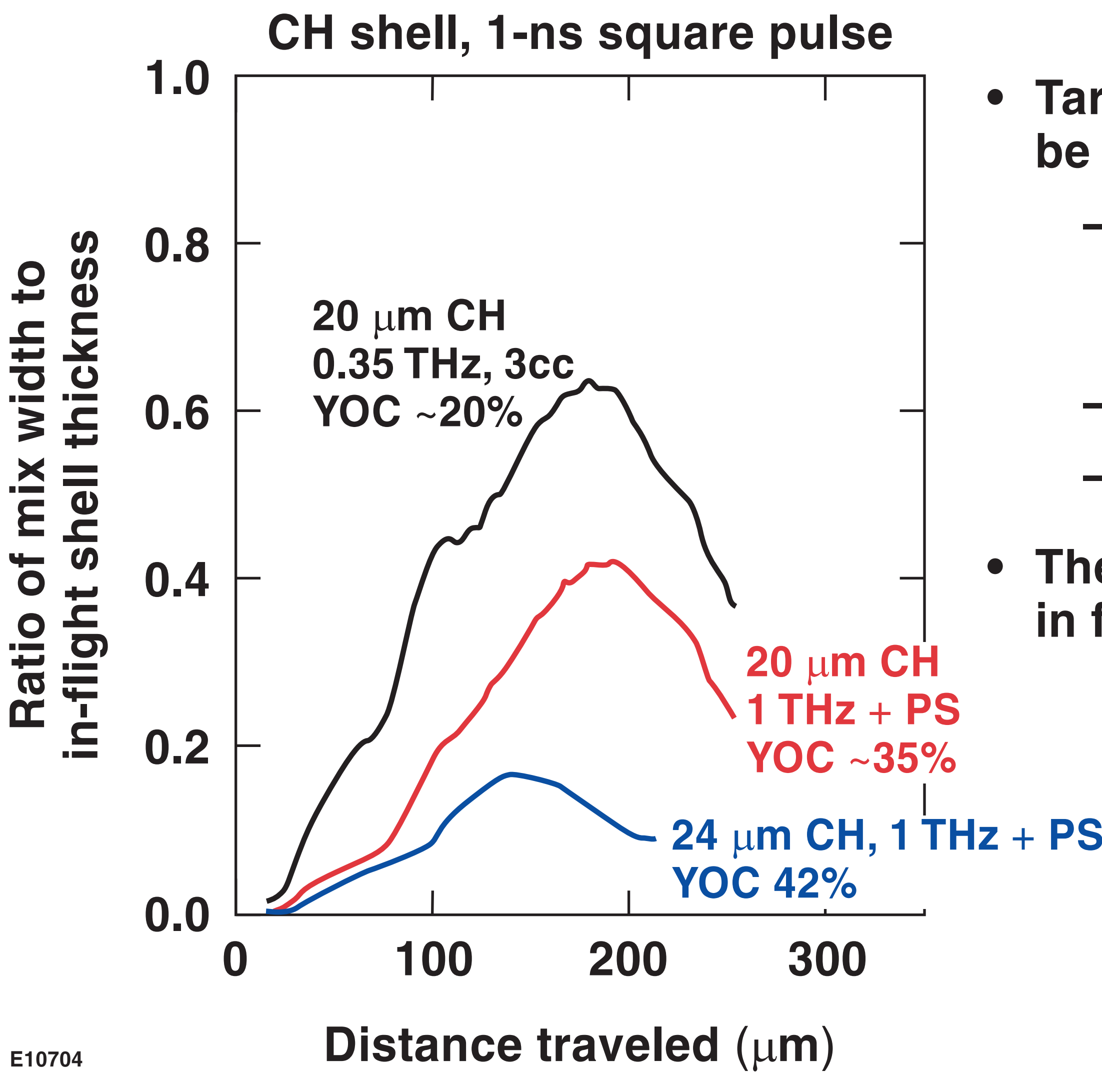
Compared to 1-D predictions:

Primary neutron yield 35% of clean 1-D
Inferred fuel and shell ρR's >85% of clean 1-D

I1197

In collaboration with MIT

Single-beam nonuniformity no longer appears to be the primary limitation of target performance



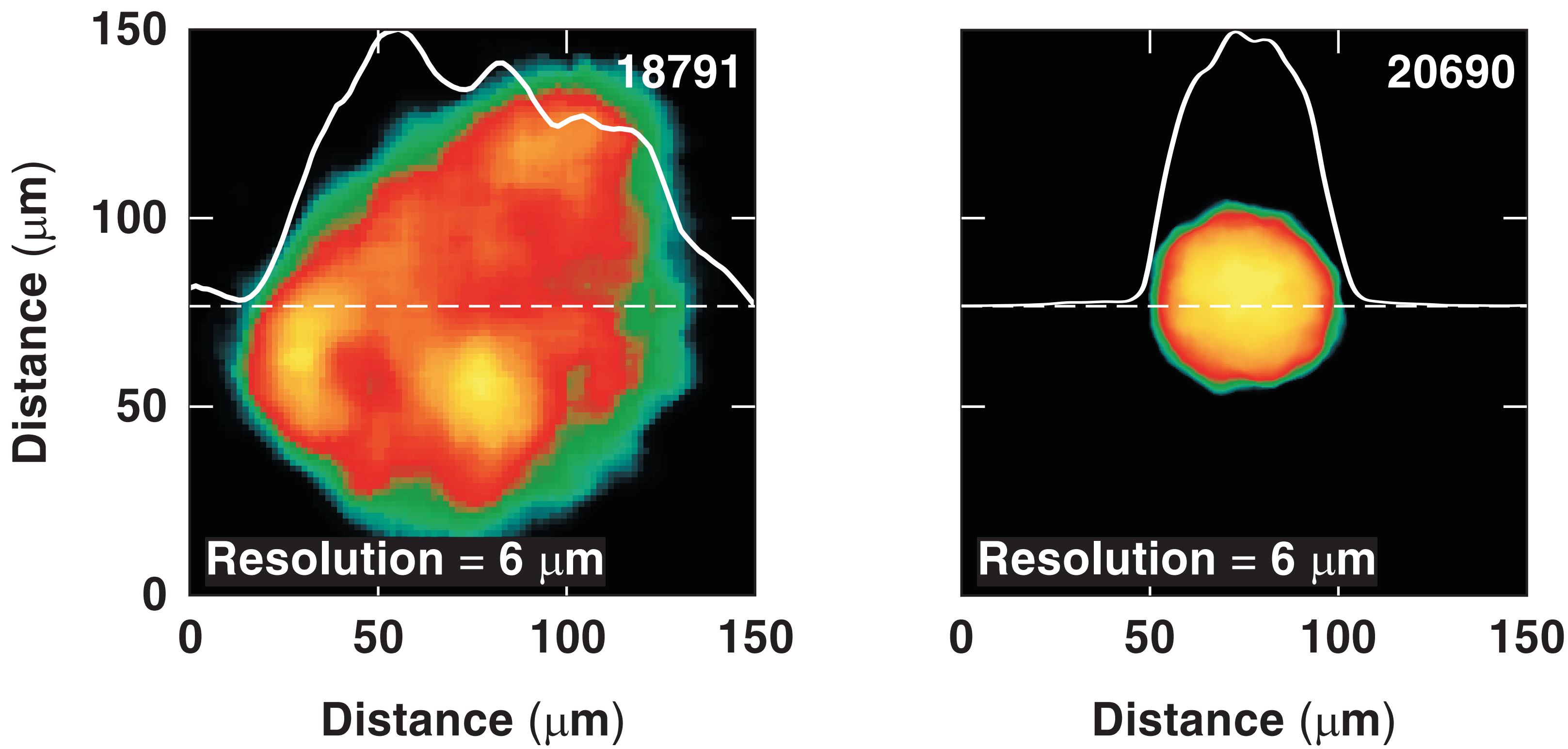
E10704

- Target performance may also be affected by
  - power imbalance (laser pulse shape, beam timing, and focus spot size)
  - effects of stalk mounting
  - target fabrication
- These effects will be studied in future experiments.

Time-resolved core images (> 3 keV) show smaller, rounder cores with 1-THz SSD and PS

UR LLE

Target: ~900-μm diam, 20 μm CH, 15 atm D_2



1/3 THz/3 color cycles
Primary yield = 8×10^{10}
Secondary yield = 1.4×10^{8}

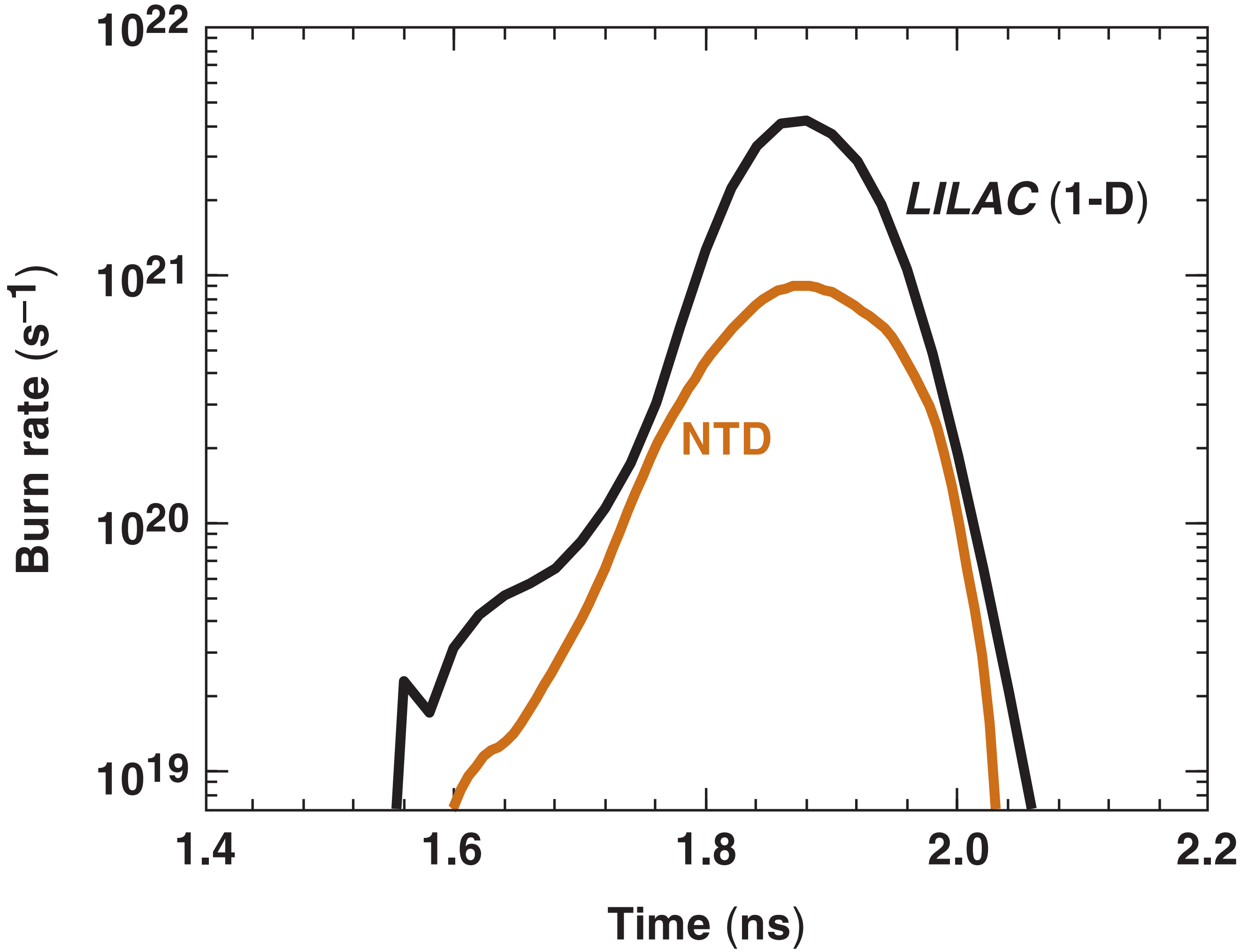
1 THz/1 color cycle + PS
Primary yield = 1.6×10^{11}
Secondary yield = 3.6×10^{8}

E10555a

HO2:003

Experiments with a 1-ns square laser pulse show no truncation of the neutron yield

UR LLE



Capsule:

- 1-mm diam.
- 20 μm CH
- 15 atm DT

Laser:

- 1-ns square
- 1-THz SSD
- Polarization smoothing

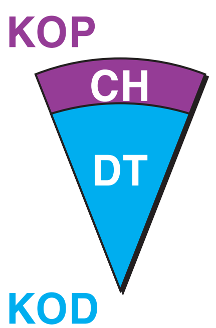
- **Measured and calculated bang times are in good agreement for all shots.**

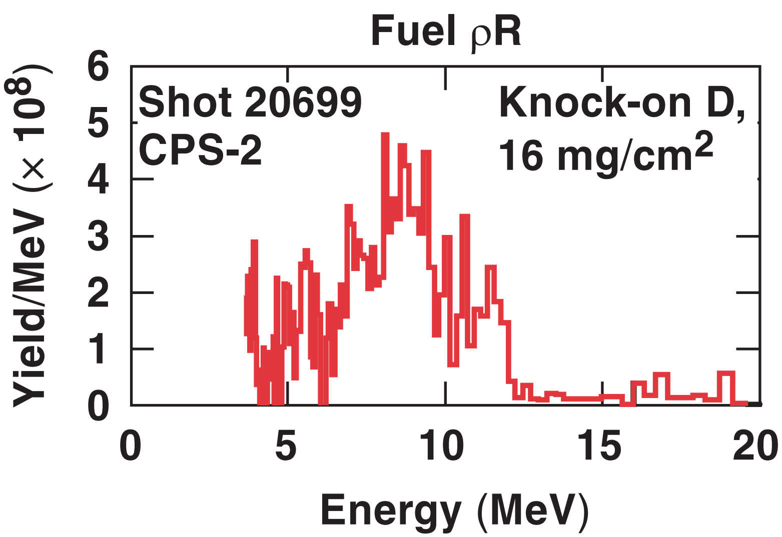
E10633a

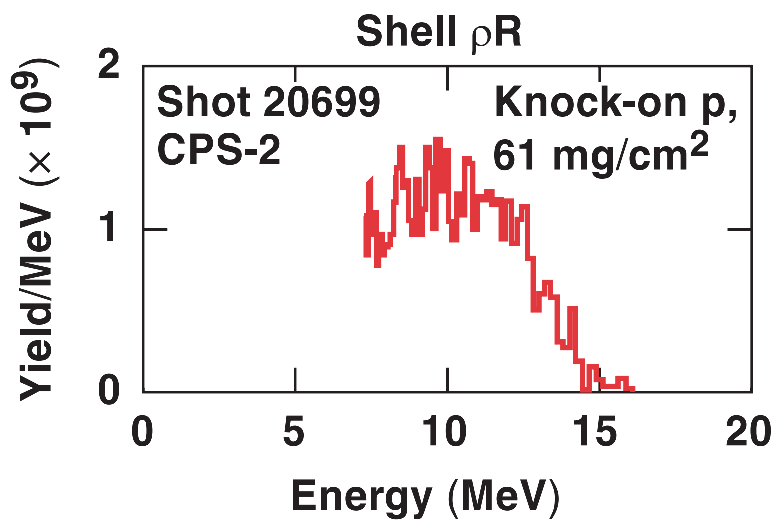
HO2.002

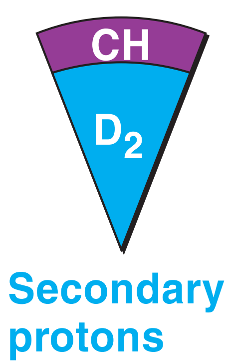
Nuclear and particle diagnostics provide a consistent picture of the core and shell conditions

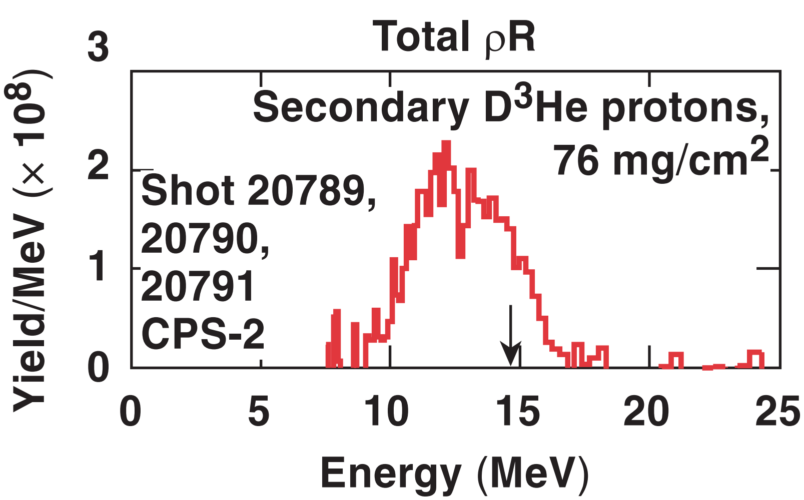
- 19-μm-CH shell, 15 atm D_2 or DT fill, 1-ns square, 23 kJ











Fuel ρR + shell ρR = total ρR

<u>Predicted</u>

Fuel 17 mg/cm^2

Shell 64 mg/cm^2

YOC ~ 35%

HO1:007, 008

I1198b

A static, five-parameter model can be constructed to reproduce experimental data

- The core conditions and mix properties are inferred from a simple, static model.
- Assumptions:
  - The core is divided into clean and mixed regions.
  - The temperature is uniform in the clean region and falls linearly in the mix region.
  - The fuel and mixed-plastic densities change linearly in the mix region.
  - Fuel mass is conserved.
- Parameters
  - Temperature at center and outer edge of mix region
  - Total fuel ρR } determines radius of clean and mix region
  - Fraction of fuel ρR in mix region } determines radius of clean and mix region
  - Amount of plastic in mix region
- The model should reproduce all core measurements.

The model produces a tightly constrained set of core properties for 15-atm-fill, 20-μm-thick shells

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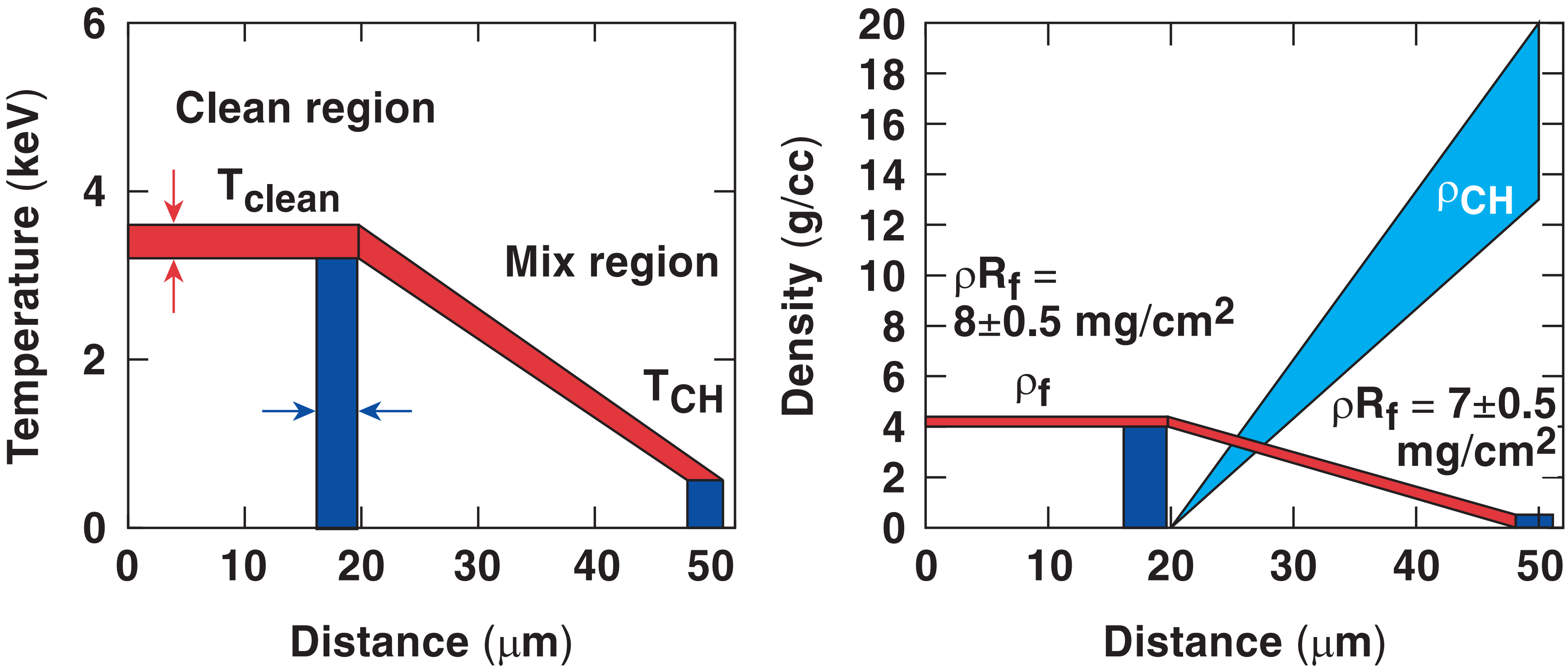
- 1-THz SSD, 1 color cycle, PS, 0.5~1 μm of original CH mixed (20% of ρR_s)



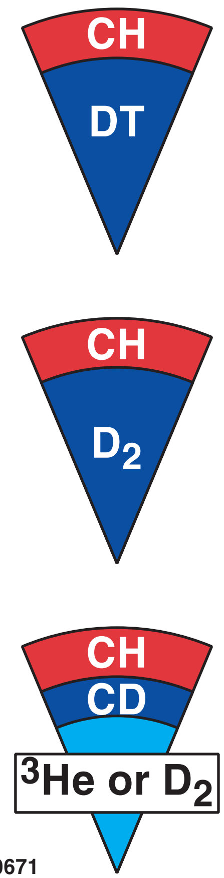
- The model should reproduce many measurements:
  - secondary particle ratios with different target (3),
  - fusion rate, $\langle T \rangle_{ion}$, radius of emission region
- The model parameters are tightly constrained by the experiments (ranges shown on graph).

TC5523a

The model reproduces many experimental observables with 1 μm of shell material mixed in the fuel

UR LLE

- 1-ns square, 23 kJ, 20-μm CH and CD shells, 15 atm fill



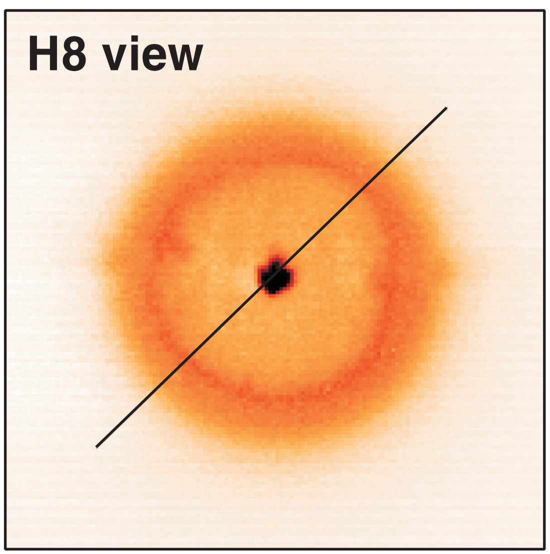
Parameter	Measurement	Model (% of expt.)
Fuel ρR (mg/cm^2)	15±2	100
T_{ion} (DT)(keV)	4.4±0.4±0.5 (sys)	86
Max: neutron burn rate (n/s)	$(9\pm1)\times10^{20}$	110
T_{ion} (D_2)(keV)	3.7±0.2±0.5 (sys)	89
Secondary neutron ratio	$(2.4\pm0.4)\times10^{-3}$	100
Secondary proton ratio	$(1.8\pm0.3)\times10^{-3}$	78
Secondary neutron ratio (D_2)	$(3.1\pm0.5)\times10^{-3}$	94
D-^{3}He proton yield (^{3}He fill)	$(1.3\pm0.2)\times10^{7}$	66
D_2 neutron yield (^{3}He fill)	$(8.5\pm0.4)\times10^{8}$	97

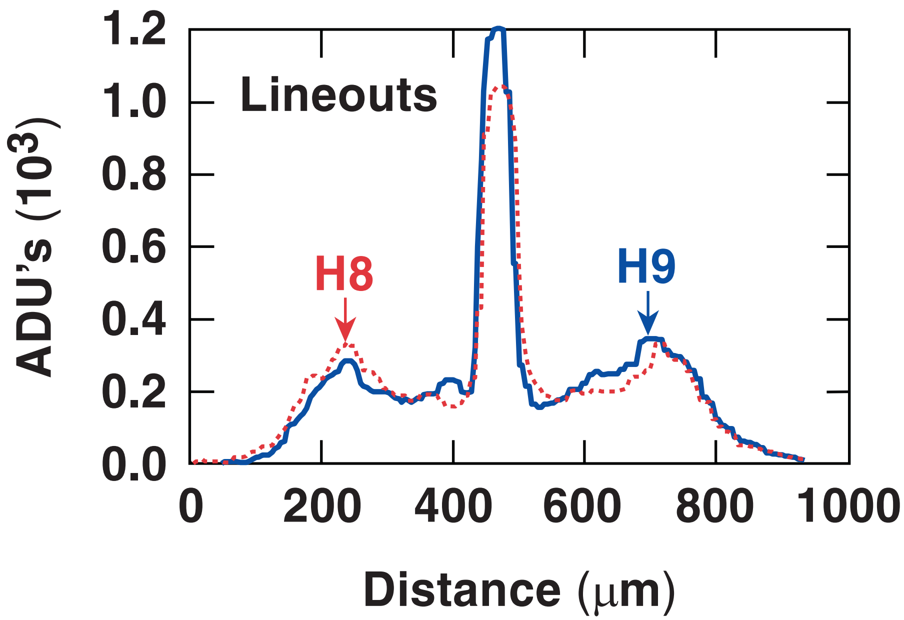
E10671

HO1:004

Initial 60-beam cryogenic D_2 target implosions on OMEGA show good performance

- 9~10-μm CD shells with ~ 100-μm ice layers have been imploded.
  - PS26, 17 kJ with 1 THz and PS
  - Layered, but not smooth ice, ~1.9-atm residual gas pressure
- Primary yield: 1~2 × 10^9, 3%~5% of 1-D
- Secondary neutron yield ratio: 0.5%~1%
- Central cores, ~50-μm diam.





E10673

Summary/Conclusions

Advances individual beam uniformity and power balance on OMEGA have greatly improved target performance

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- For CR~15 targets (20 μm CH):
  - Fuel and shell areal densities are close to clean 1-D predictions.
  - Primary neutron yields are 35% of clean 1-D predictions.
  - Model shows small amounts of mix.
  - Single-beam nonuniformity is probably not the primary limitation on target performance.
- A wide variety of target types and fill pressures are utilized:
  - Provide self-consistency checks on diagnostic results;
  - Constrain core and fuel–shell mix profiles.
- The first 60-beam cryogenic implosions have been performed on OMEGA.

These results provide optimism for cryogenic target performance.