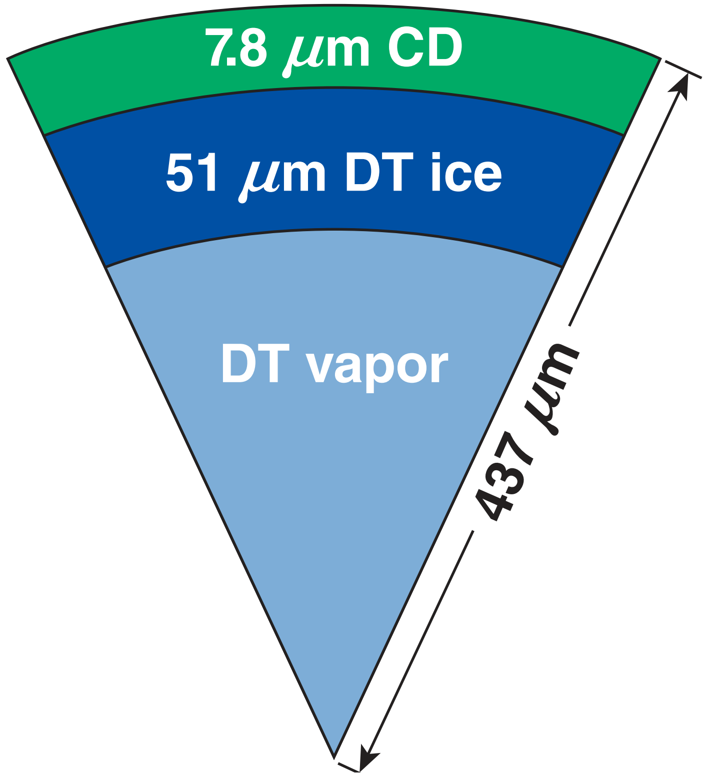
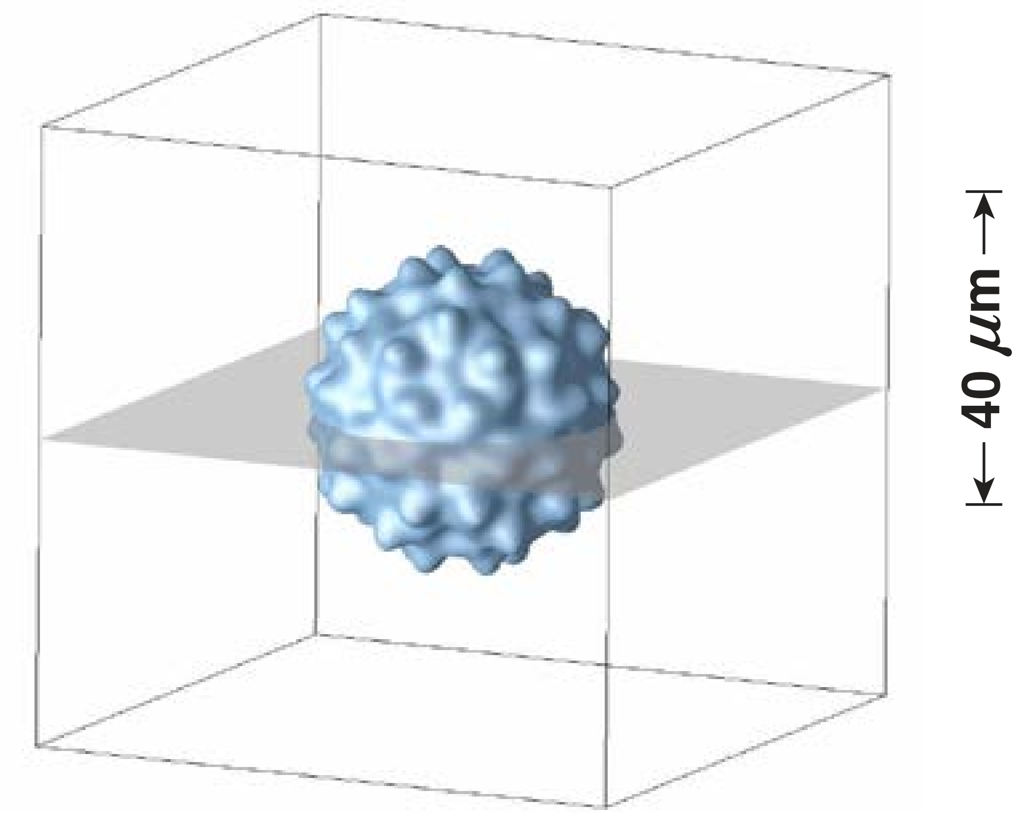
Three-Dimensional Hydrodynamic Simulations of OMEGA implosions

OMEGA direct-drive cryogenic target



Shape of hot spot at peak neutron production



I. V. Igumenshchev
University of Rochester
Laboratory for Laser Energetics

58th Annual Meeting of the
American Physical Society
Division of Plasma Physics
San Jose, CA
31 October–4 November 2016

Summary

Consistent interpretation of OMEGA direct-drive implosions indicates significant effects of large-scale asymmetries

- Several x-ray and neutron-based observations show the presence of large-scale asymmetries in direct-drive cryogenic and room-temperature OMEGA implosions
- Three-dimensional *ASTER** simulations using measured low-ℓ-mode seeds reproduce these observations
- Simulations indicate that asymmetries resulting from measured target offset, beam-to-beam power imbalance, and ice-shell nonuniformities reduce the stagnation pressure by 40%

Three-dimensional simulations are essential to guide physics campaigns and engineering advancements on the OMEGA laser.

---

*I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).

Collaborators

D. T. Michel, K. S. Anderson, E. M. Campbell, D. H. Edgell, R. Epstein, C. J. Forrest,
V. Yu. Glebov, V. N. Goncharov, J. P. Knauer, F. J. Marshall, R. L. McCrory,
P. B. Radha, S. P. Regan, T. C. Sangster, and C. Stoeckl

University of Rochester
Laboratory for Laser Energetics

R. C. Shah

Los Alamos National Laboratory

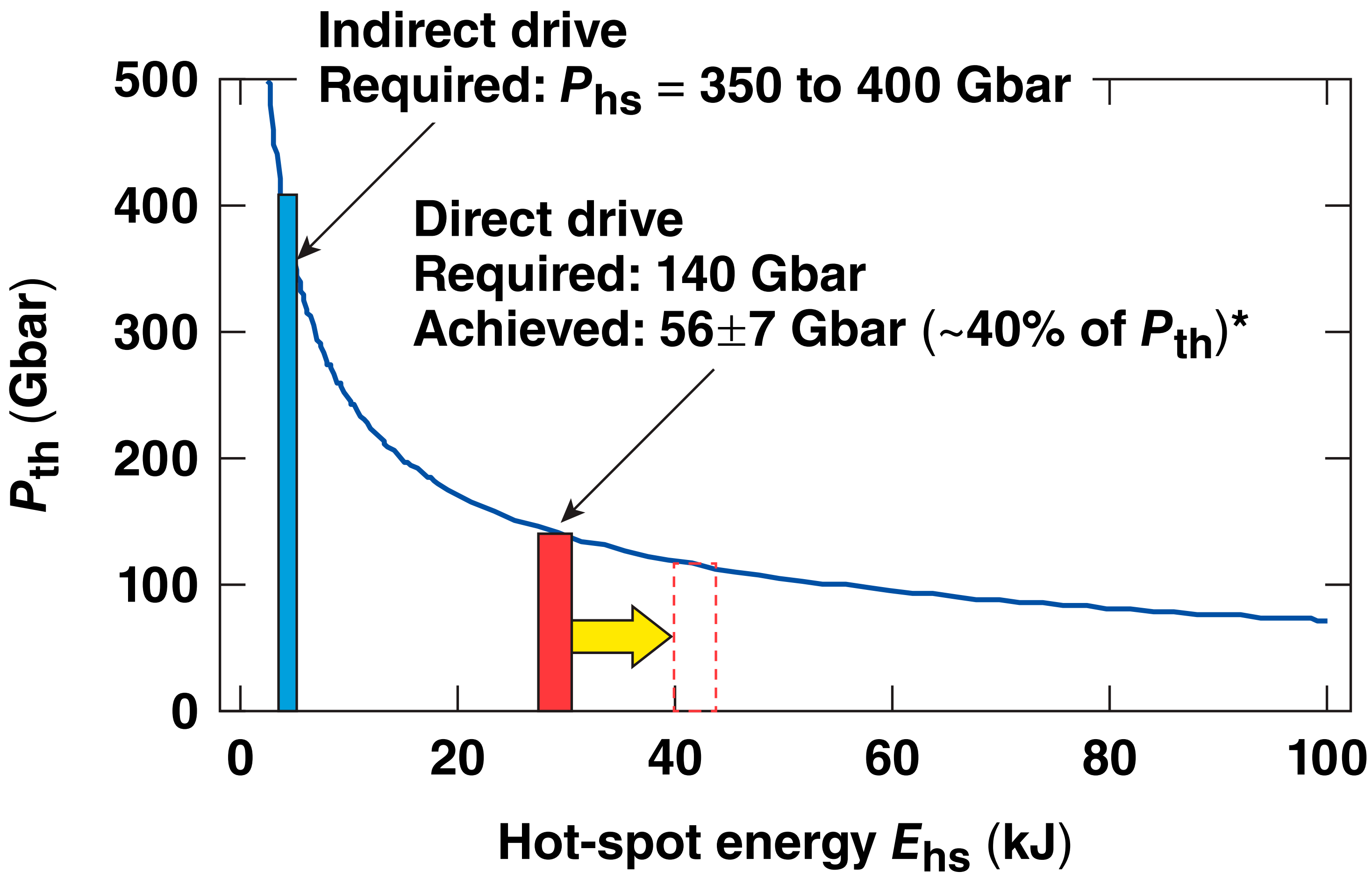
A. J. Schmitt, D. Fyfe, and S. Obenschain

Naval Research Laboratory

Outline

- Introduction
- Measured evidences of large-scale asymmetries
- 3-D hydrodynamic codes at LLE
- *ASTER* simulations of drive asymmetry in room-temperature OMEGA implosions
- Simulations of a cryogenic OMEGA implosion
- Path forward

Direct drive requires a factor of 3 lower hot-spot pressure for ignition than indirect drive


Indirect drive
Required: P_{hs} = 350 to 400 Gbar

Direct drive
Required: 140 Gbar
Achieved: 56±7 Gbar (~40% of P_{th})*

- **Pressure threshold for ignition**

$$\boxed{P_{th} \sim 1/\sqrt{E_{hs}}}$$

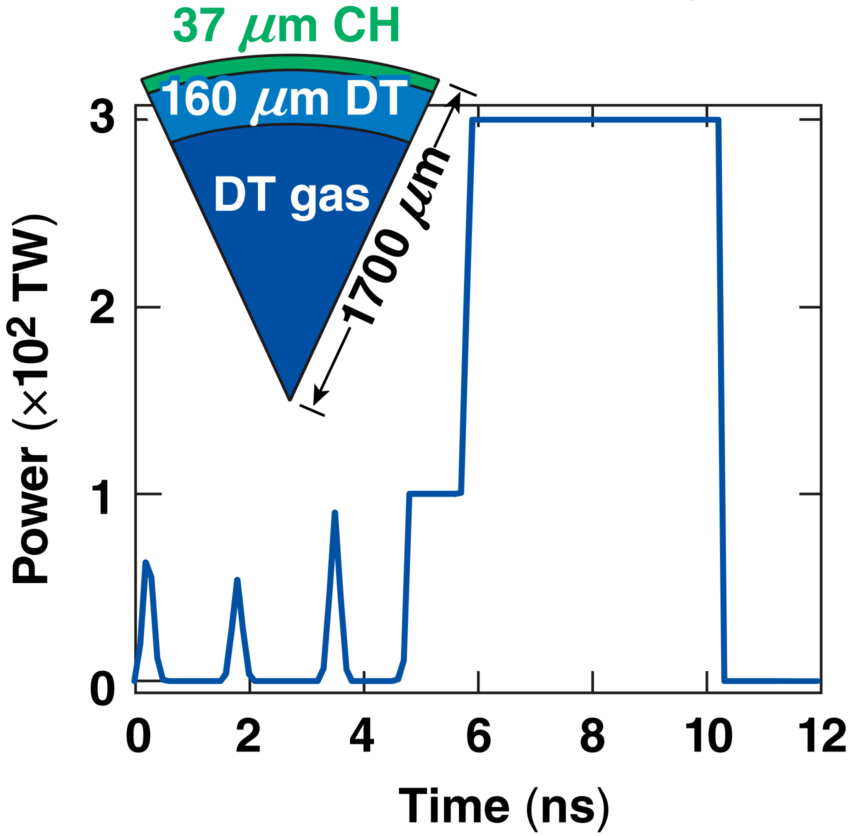
Direct-drive ignition: CR > 22 and P_{hs} > 120 Gbar
Indirect-drive ignition: CR = 30 to 40 and P_{hs} > 350 Gbar

CR: convergence ratio

*S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016).

OMEGA cryogenic implosions are hydrodynamically scaled from NIF-scale ignition designs

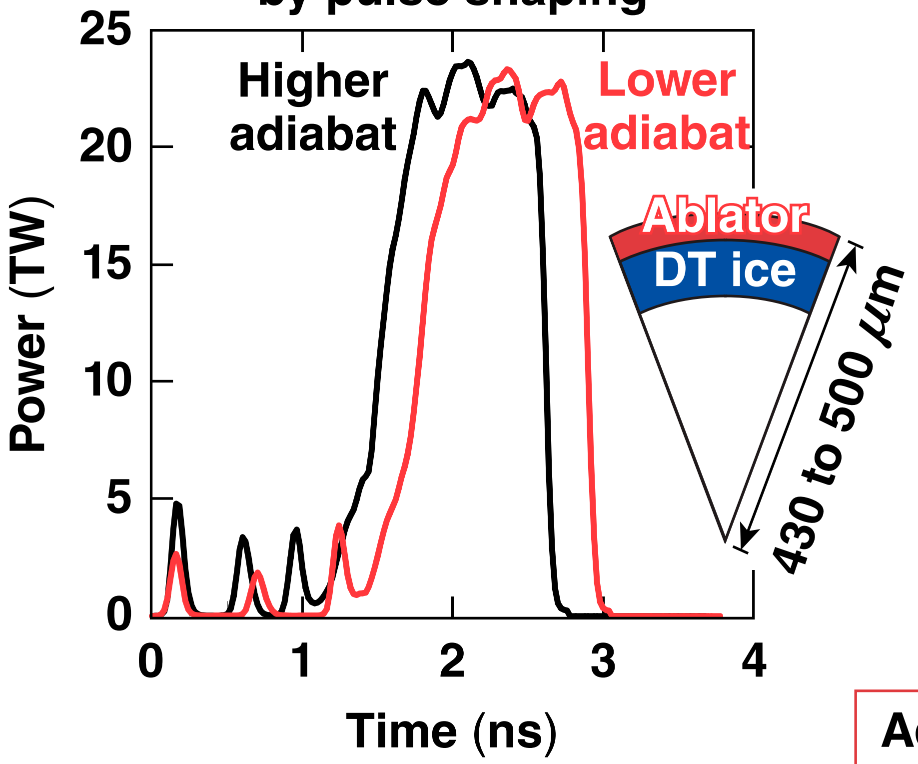
1.5-MJ, spherically symmetric direct-drive design



- $V_{\mathrm{imp}} = 3.8$ to 4×10^7 cm/s
  Adiabat $\alpha = 1.6$ to 3
  $\mathrm{IFAR}_{2/3} = 20$ to 25
  CR = 20 to 23

26- to 29-kJ OMEGA cryogenic design

Adiabat and IFAR are controlled by pulse shaping



- V_{imp} and IFAR are controlled by varying the ablator (7.5 to 12 μm) and fuel thickness (40 to 66 μm)

Adiabat
$\alpha = P/P_{\mathrm{Fermi}}$

IFAR = shell radius/shell thickness

IFAR: in-flight aspect ratio

TC12314g

Achieving $P_{\text{hs}} \sim P_{\text{th}}$ requires understanding and mitigating various sources of performance degradation in OMEGA implosions

1-D physics

- Uncertainties in equation of state (EOS)
  - strongly coupled plasma
  - shell release

J. P. Knauer *et al.*, NO5.00008, this conference.

- Hydrodynamic efficiency
  - effect of cross-beam energy transfer (CBET)
  - heat transport

P. B. Radha *et al.*, NO5.00005;
J. A. Marozas *et al.*, NO5.00009, this conference.

A. K. Davis *et al.*, NO8.00007, this conference.

- Preheat
  - radiation from hot corona
  - energy particles as a result of laser–plasma interactions (LPI)

A. R. Christopherson *et al.*, NO5.00007, this conference.

J. A. Delettrez *et al.*, UO9.00015, this conference.

- Small-scale mix
  - laser imprint
  - target defects

D. T. Michel *et al.*, TO5.00006; S. X. Hu *et al.*, JO5.00001;
A. Shvydky *et al.*, JO5.00003, this conference.

S. P. Regan *et al.*, TO5.00004, this conference.

- **Large-scale asymmetries**

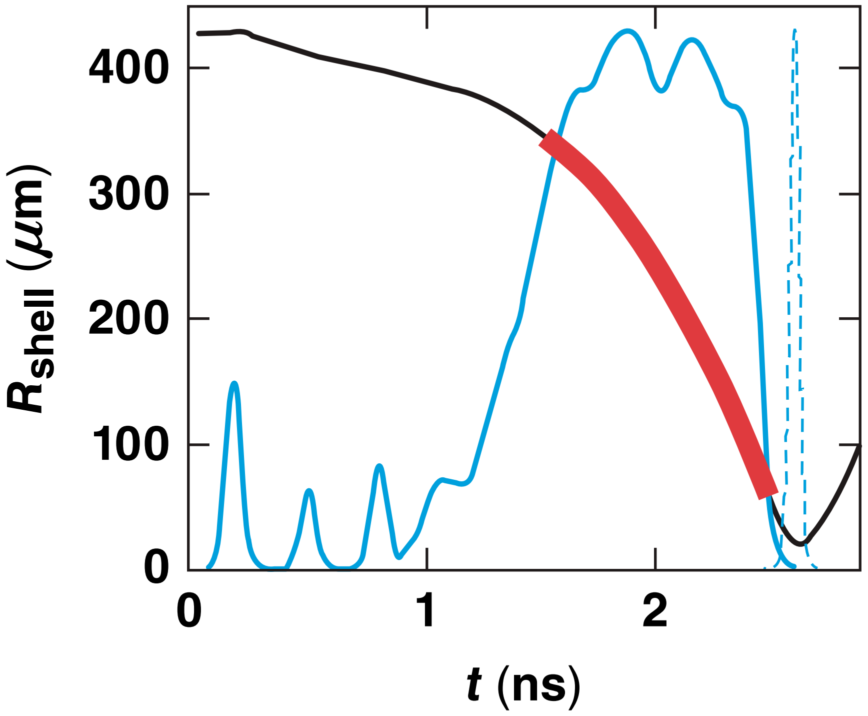
This talk; K. S. Anderson *et al.*, NO5.00011;
K. M. Woo *et al.*, TO5.00015, this conference.

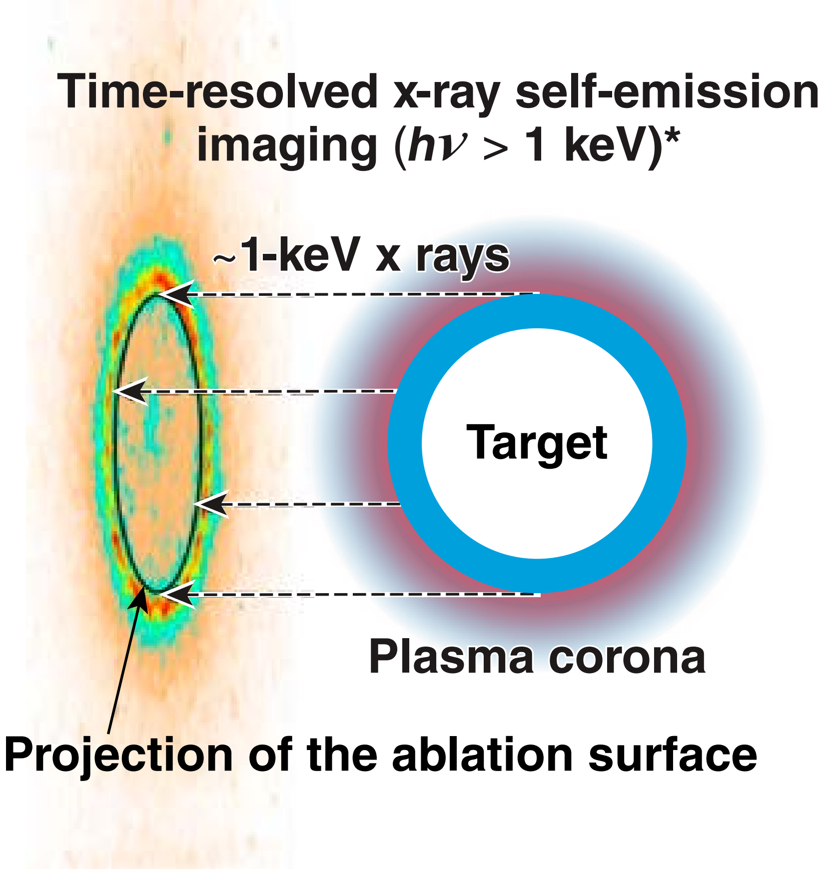
Outline

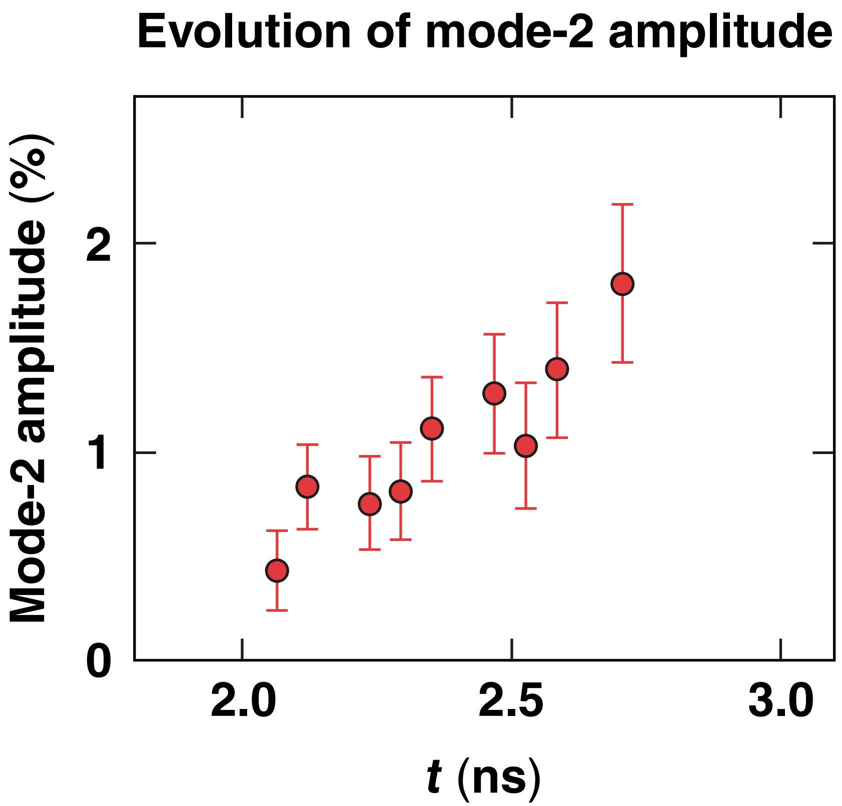
- Introduction
- **Measured evidences of large-scale asymmetries**
- 3-D hydrodynamic codes at LLE
- *ASTER* simulations of drive asymmetry in room-temperature OMEGA implosions
- Simulations of a cryogenic OMEGA implosion
- Path forward

Measurements show large-scale asymmetries in OMEGA implosions

Target asymmetry during laser drive







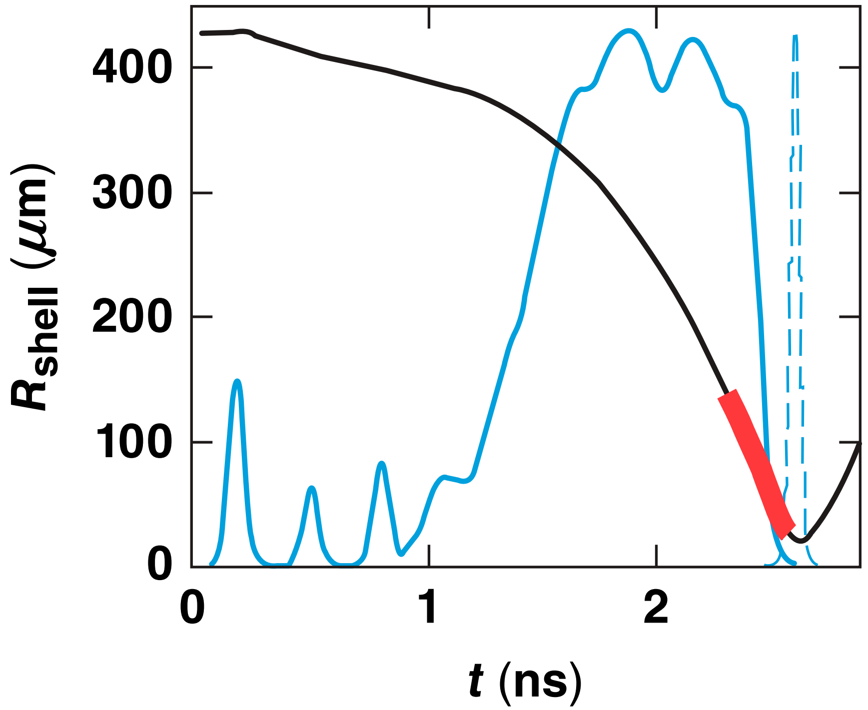
TC13117

---

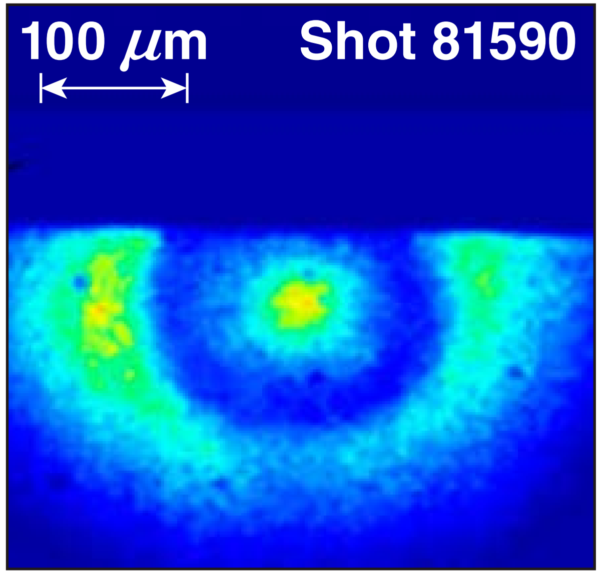
*D. T. Michel *et al.*, Rev. Sci. Instrum. 83, 10E530 (2012).

Measurements show large-scale asymmetries in OMEGA implosions

Asymmetry of dense shells before stagnation



Time-resolved x-ray backlighting of cryogenic implosions ($h\nu$ ~ 1.9 keV)

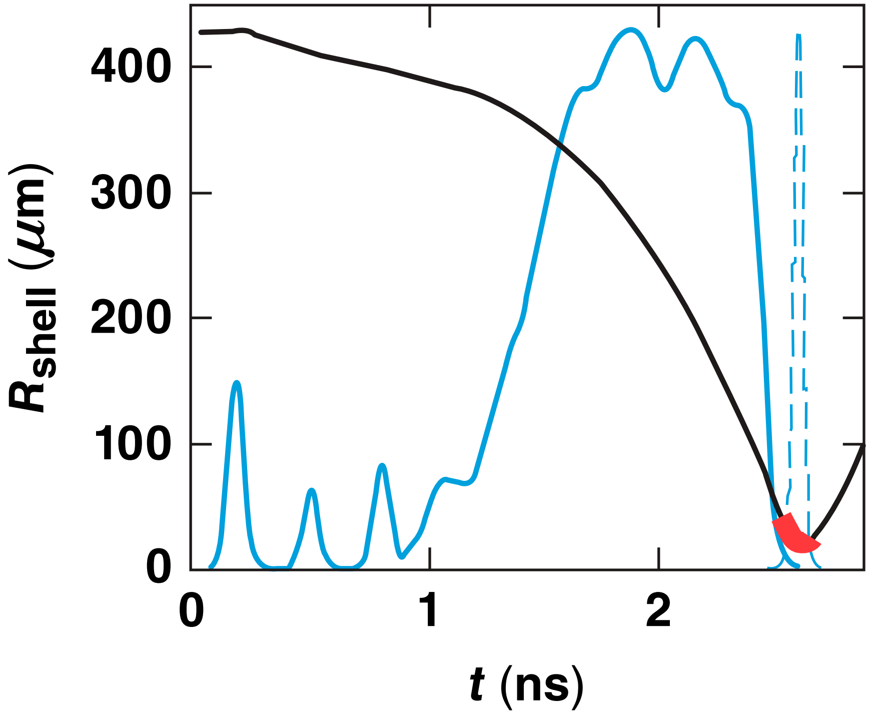


t_{bang} – 100 ps

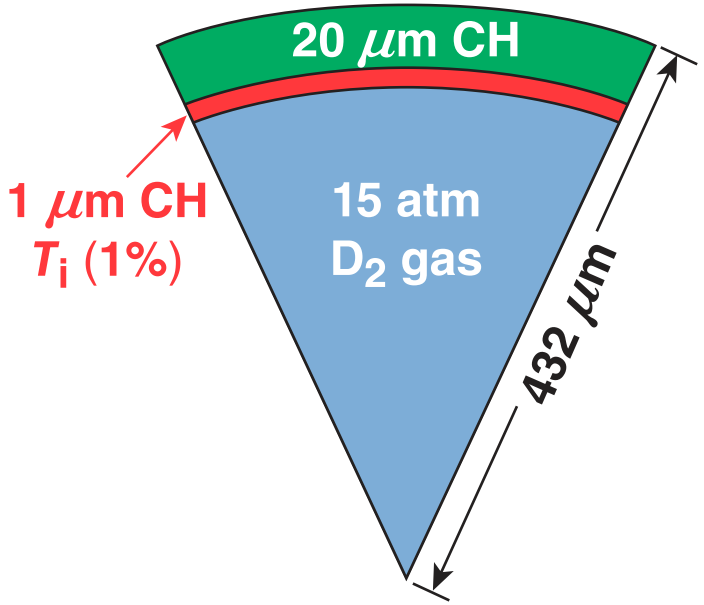
C. Stoeckl, NI2.00004, this conference (invited).

Measurements show large-scale asymmetries in OMEGA implosions

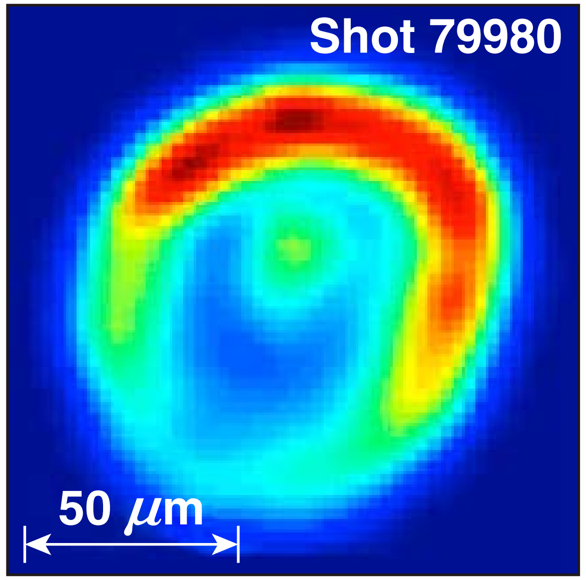
Implosion asymmetry near bang time*



D_2-filled Ti-doped plastic shell target



Time-resolved T_i He-β emission image (~5.5 keV)

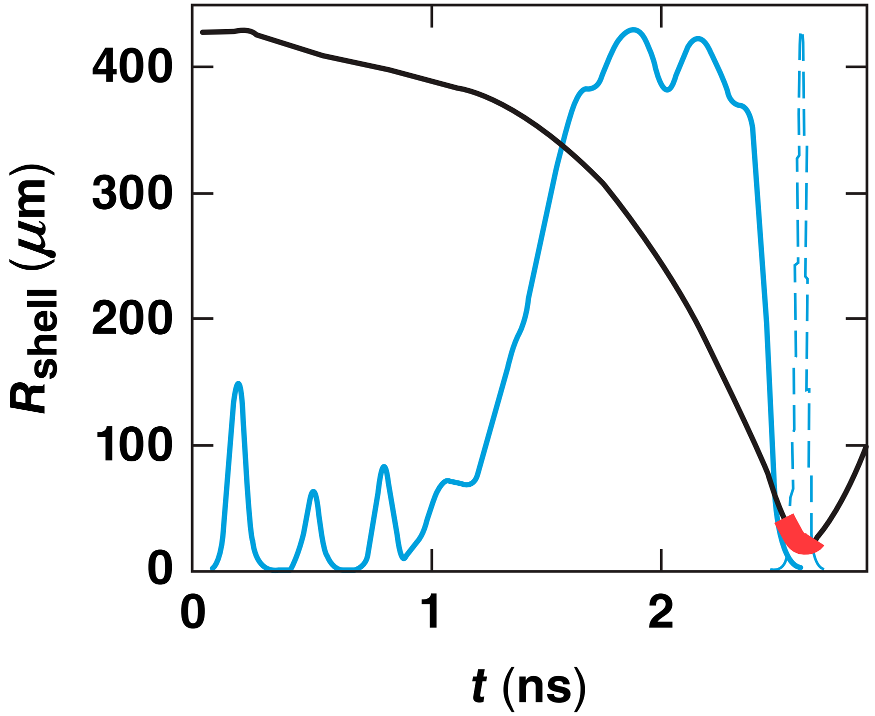


---

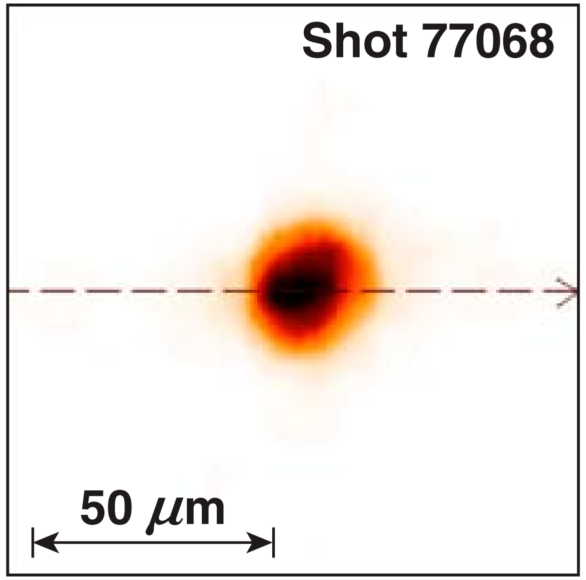
*R. Shah *et al.*, GO5.00001, this conference.

Measurements show large-scale asymmetries in OMEGA implosions

Time-integrated and time-resolved x-ray imaging of hot spot



GMXI (4 to 8 keV)*



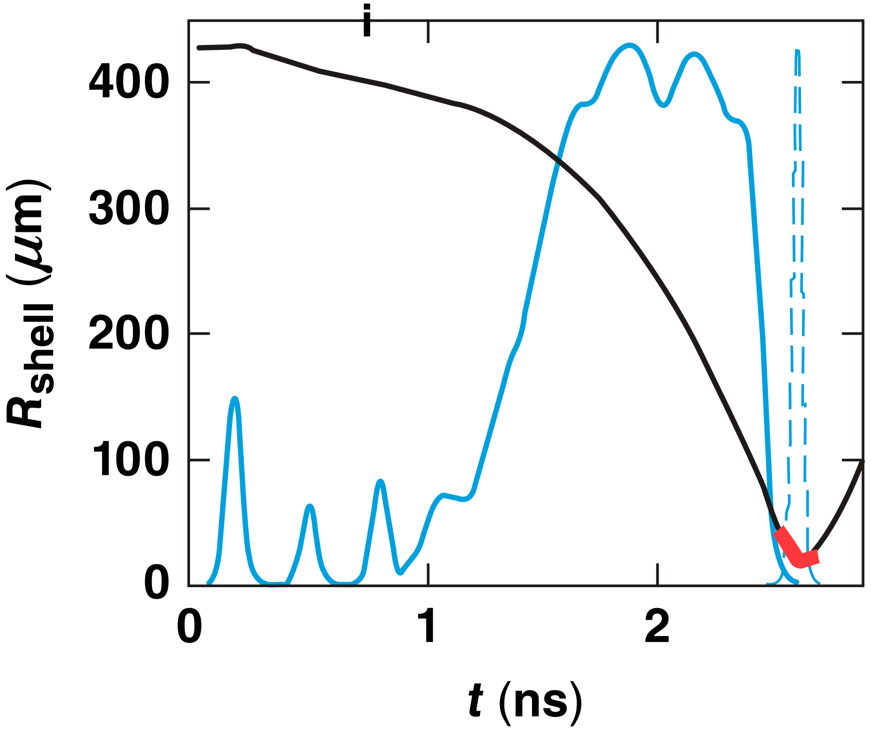
TC13114c

GMXI: gated monochromatic x-ray imager

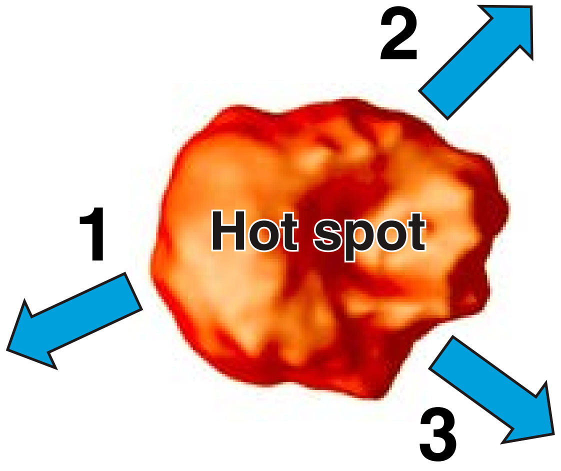
*F. J. Marshall and J. A. Oertel, Rev. Sci. Instrum. 68, 735 (1997).

Measurements show large-scale asymmetries in OMEGA implosions

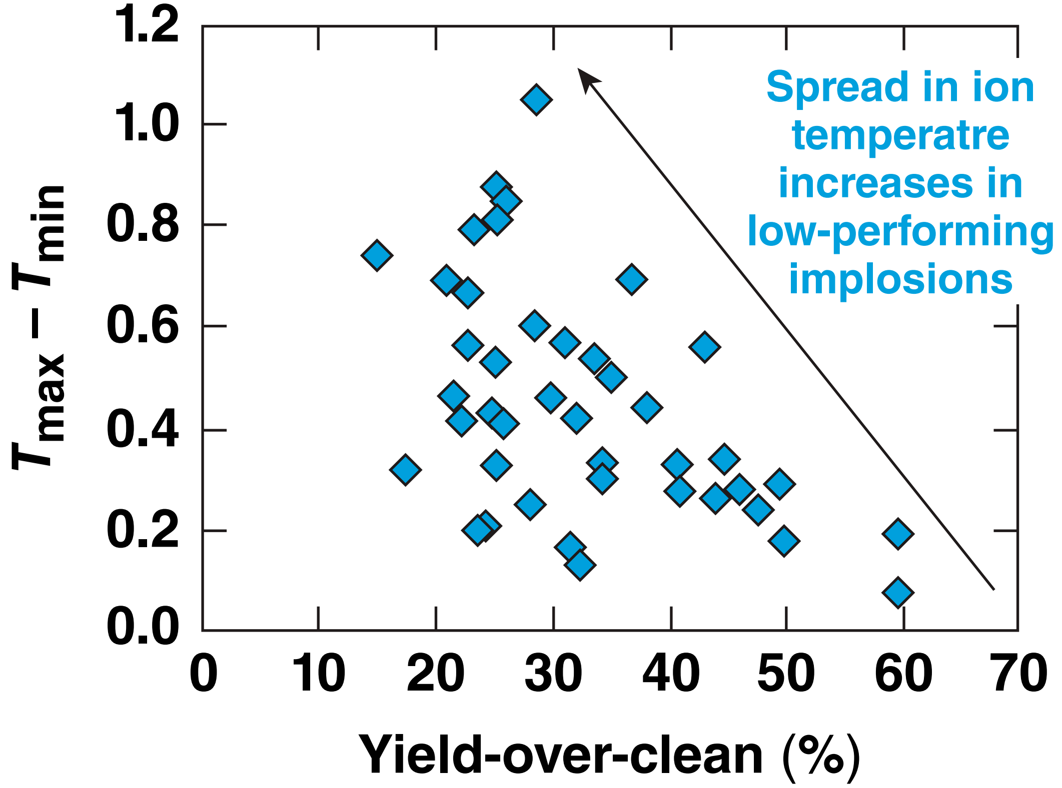
Directional variation of neutron data



Measurement in three directions



$\langle T_i \rangle_n$ inferred from DT-neutron spectra



$\langle T_i \rangle_n$ includes the flow effect*

$$\langle T_i \rangle_n = T_i + 2/3\, m_i V_f^2$$

---

*T. J. Murphy, Phys. Plasmas 21, 072701 (2014).

Outline

- Introduction
- Measured evidences of large-scale asymmetries
- **3-D hydrodynamic codes at LLE**
- *ASTER* simulations of drive asymmetry in room-temperature OMEGA implosions
- Simulations of a cryogenic OMEGA implosion
- Path forward

Two 3-D codes are being used in LLE to simulate direct-drive (DD) implosions

***HYDRA*[†]**

- **Established inertial confinement fusion (ICF) and high-energy-density physics (HEDP) community code**
- **DD-relevant physics packages under development**
  - **nonlocal heat transport**
  - **noise-free 3-D ray trace for laser deposition**
  - **CBET**

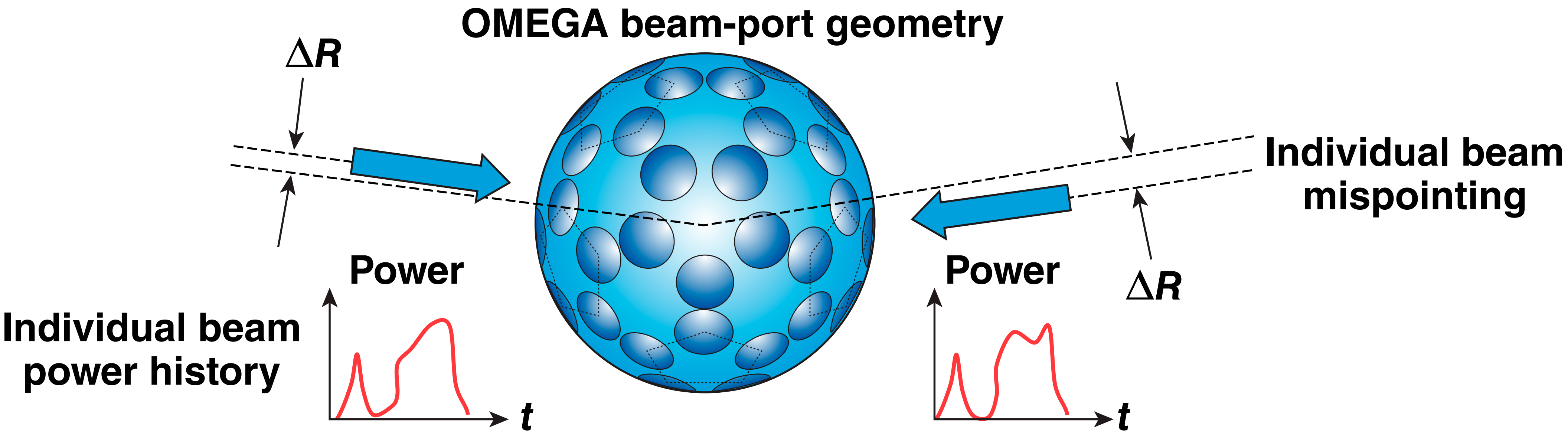
***ASTER*[‡]**

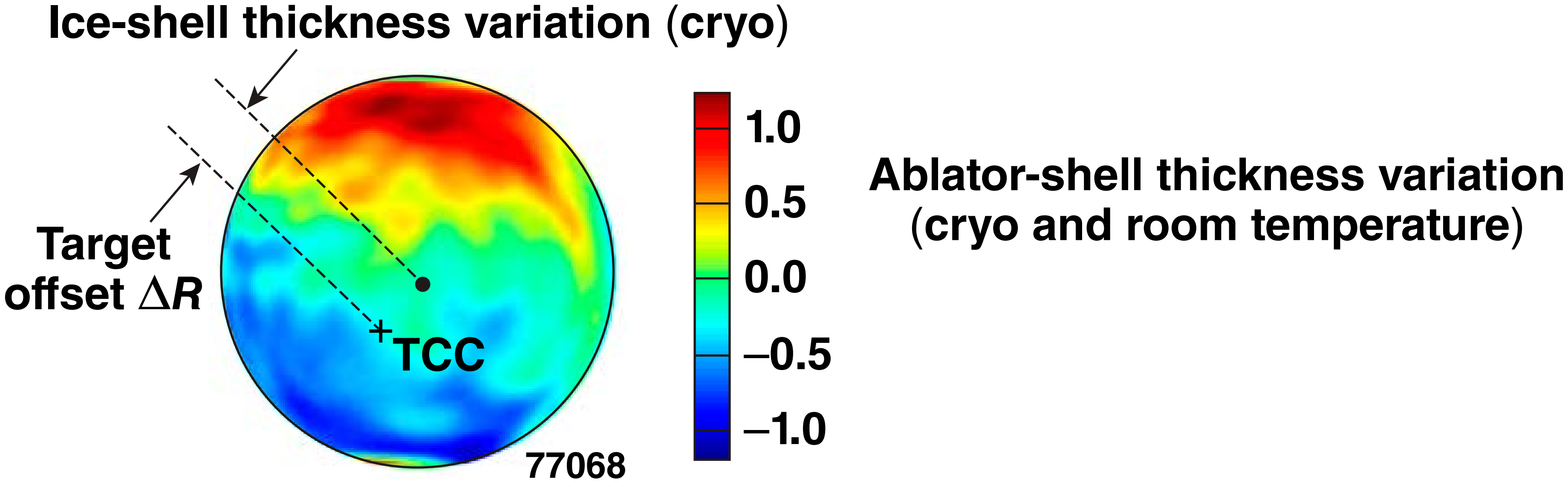
- **Eulerian code optimized for DD implosions**
- **Uses simplified models for**
  - **heat transport (flux-limited Spitzer)**
  - **3-D ray trace with CBET (spherically symmetric corona)**
- **Used to interpret and guide DD implosion experiments on OMEGA**

K. S. Anderson *et al.*, NO5.00011, this conference.
A. Shvydky *et al.*, JO5.00003, this conference.
[†] M. M. Marinak *et al.*, Phys. Plasmas 8, 2275 (2001).
[‡] I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).

TC13115

Measured sources of nonuniformity are used as input to *ASTER*





- Exact illumination nonuniformities on target are not well known

---

TCC: target chamber center

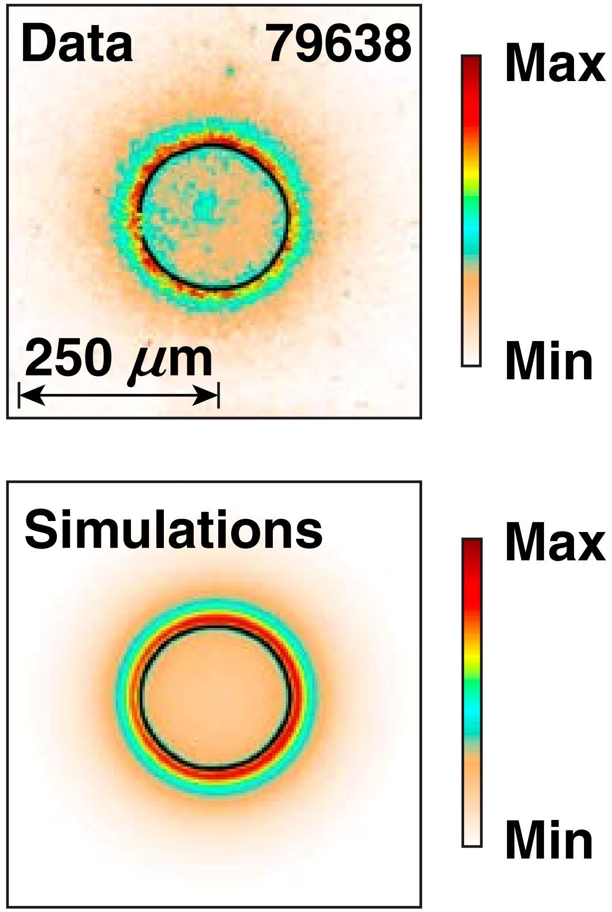
Outline

- Introduction
- Measured evidences of large-scale asymmetries
- 3-D hydrodynamic codes at LLE
- ***ASTER*** **simulations of drive asymmetry in room-temperature OMEGA implosions**
- Simulations of a cryogenic OMEGA implosion
- Path forward

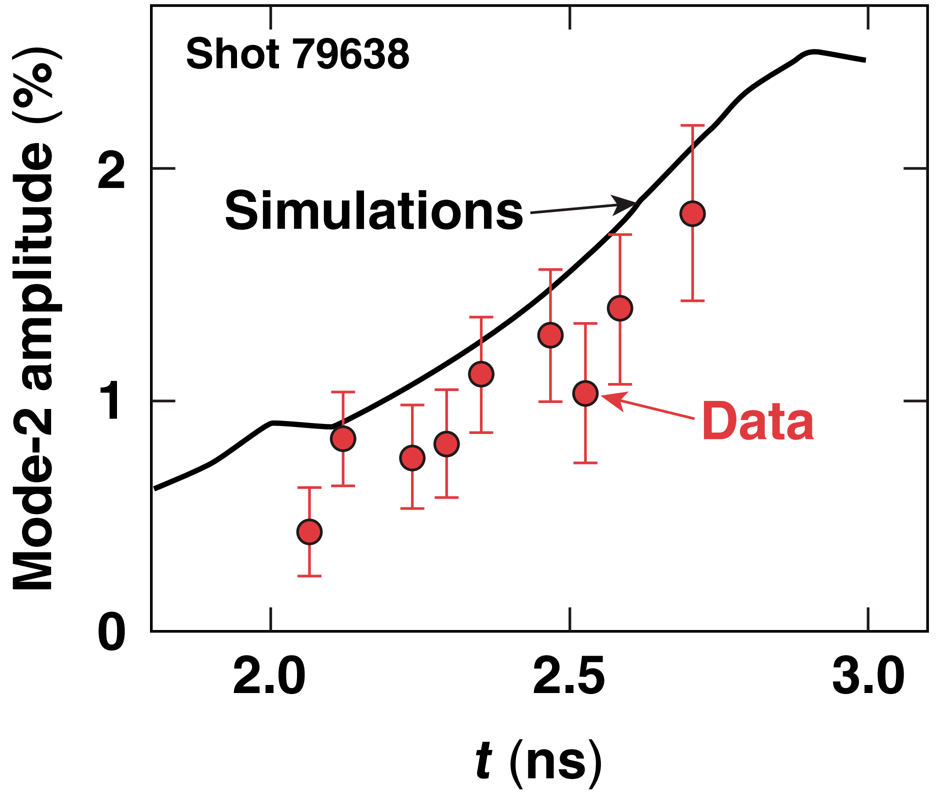
Measured mode 2 from drive asymmetry is modeled well in simulations

- **Room-temperature implosions**
  - **no ice-shell nonuniformity**
  - **no offset (<5 μm)**

Self-emission images at *t* = 2.7 ns



Evolution of mode-2 amplitude

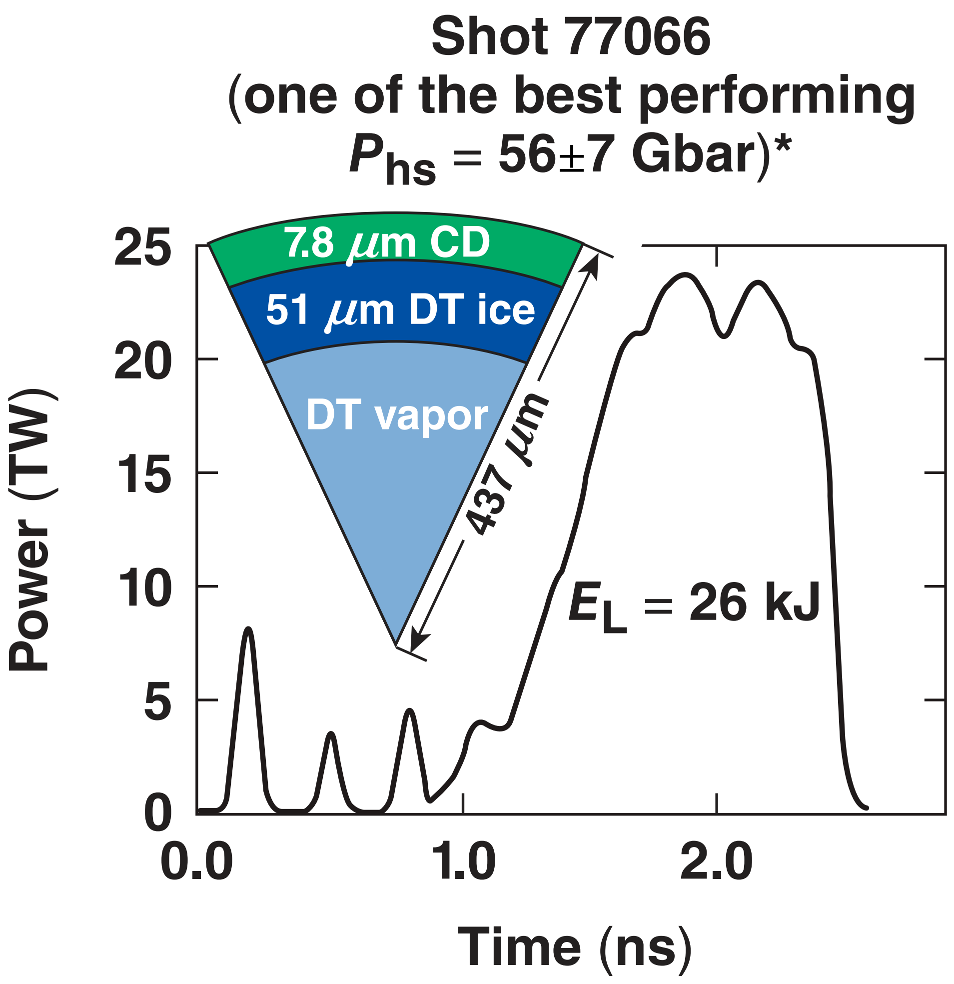


- **Phase of mode 2 does not change in time but is different in experiment and simulations (will be addressed later)**

Outline

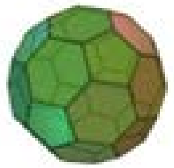
- Introduction
- Measured evidences of large-scale asymmetries
- 3-D hydrodynamic codes at LLE
- *ASTER* simulations of drive asymmetry in room-temperature OMEGA implosions
- **Simulations of a cryogenic OMEGA implosion**
- Path forward

Cryogenic implosions are simulated assuming all known sources of large-scale implosion asymmetry



α = 3.2, IFAR ≈ 24

Included (measured) sources



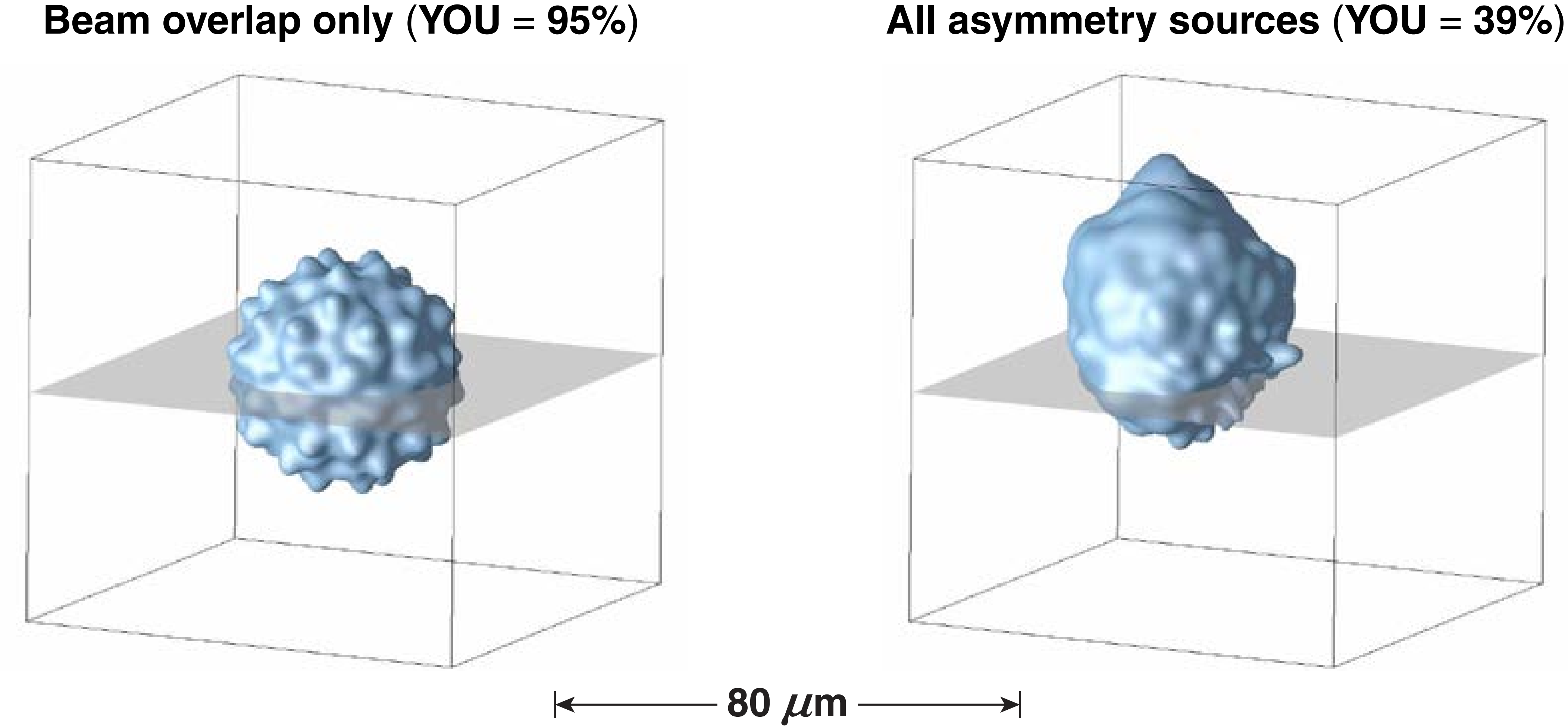
- Beam overlap
- 4-μm (±3-μm) target offset
- Ice thickness ±2 μm (bottom thinner)
- Beam-to-beam power variation (power history)
- Beam mispointing (σ_{rms} = 8.4 μm)

P. W. McKenty *et al.*, TO5.00011, this conference.
D. Cao *et al.*, TO5.00012, this conference.
K. S. Anderson *et al.*, NO5.00011, this conference.
*S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016).

TC13124

Large-scale asymmetry in the implosion core causes deformation and displacement of the hot spot

Three-dimensional view of the hot spot (surface T_i = 1 keV) at peak neutron production


Beam overlap only (YOU = 95%)

All asymmetry sources (YOU = 39%)

80 μm

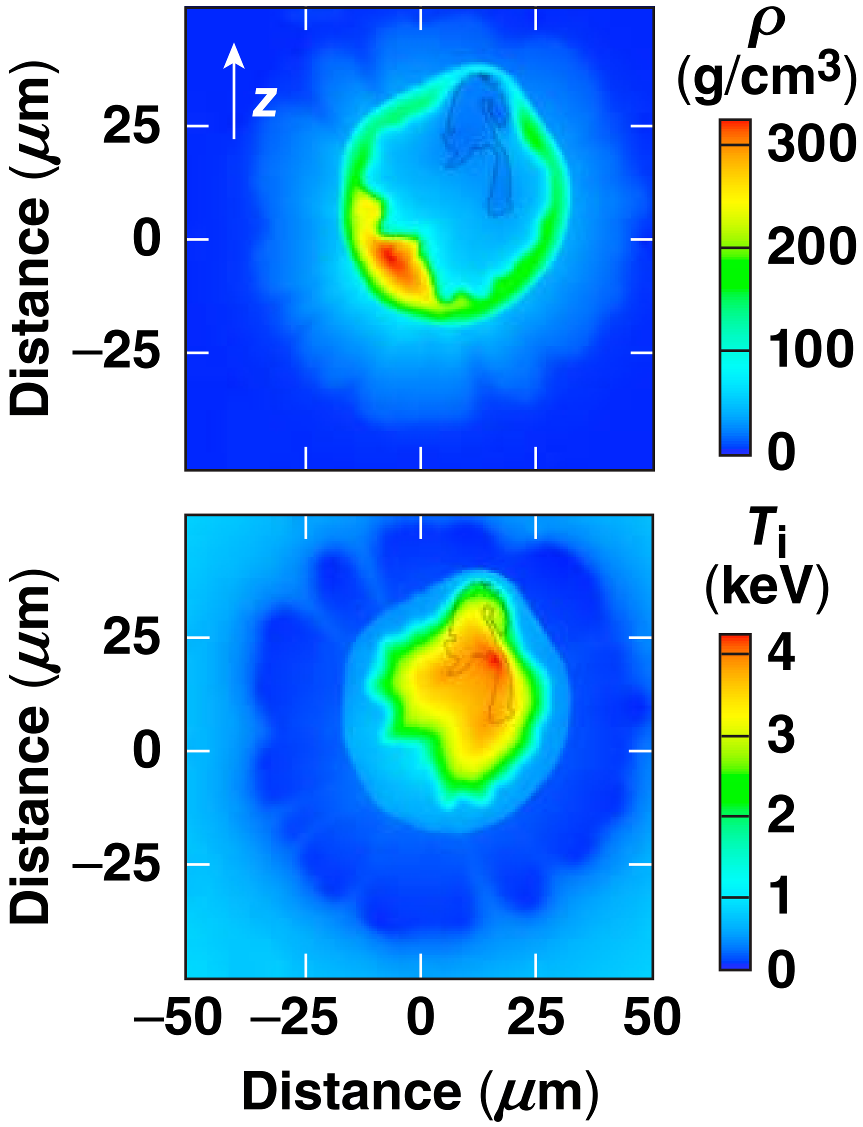
TC13125

YOU: yield-over-uniform

Simulations accurately predict reduction in implosion performance

Meridional cut views at $\varphi = 83°$

Target at peak neutron production, $t = 2.664$ ns



Summary of performance

	Experiment	Simulations
Neutron yield (relative to 1-D)	0.32	0.39
P_{hs} (relative to 1-D)	0.56	0.64

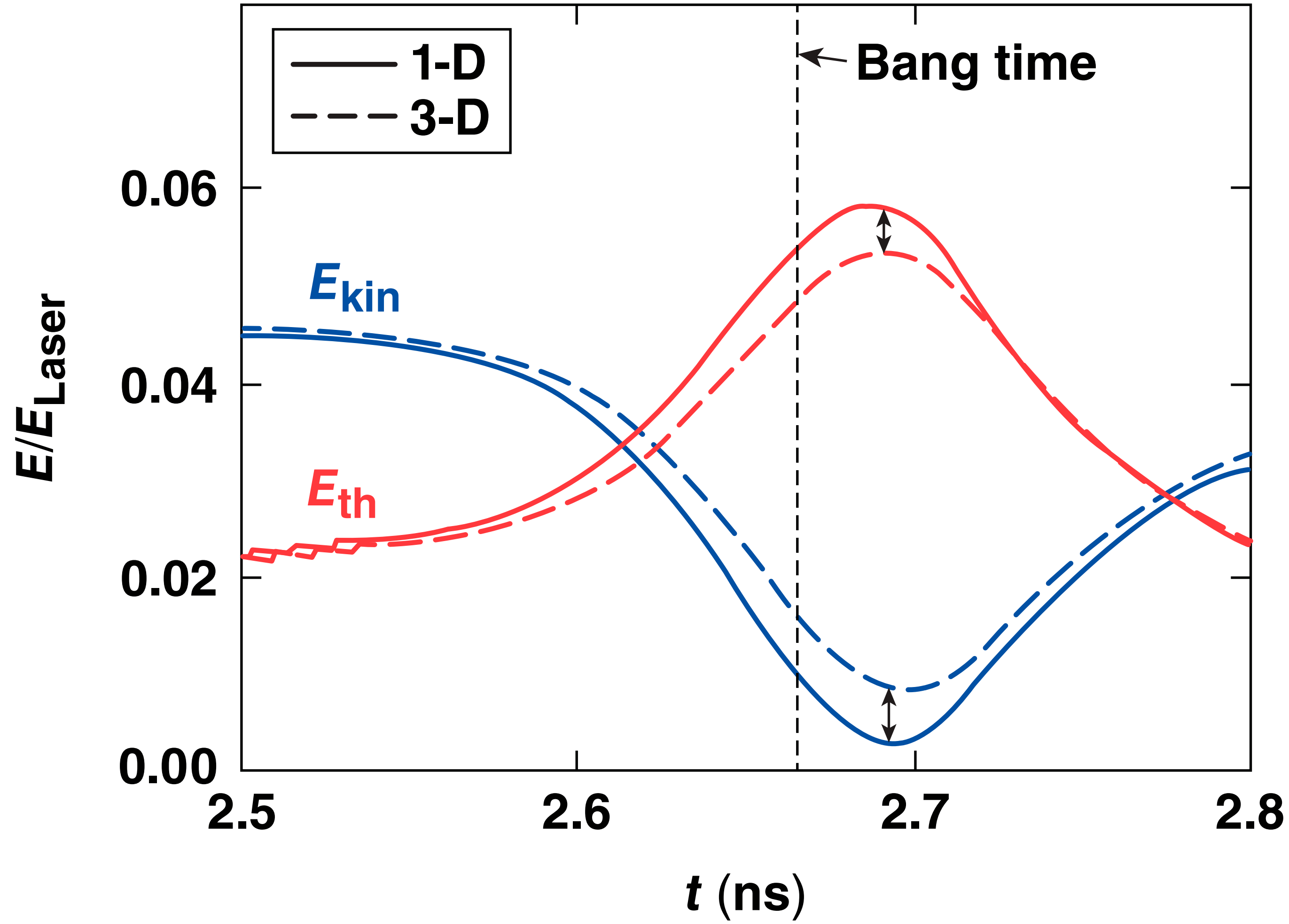
Performance reduction is caused by

- Excessive heat losses by the hot spot $\langle T_i \rangle_n$ = 3.39/3.03 keV (1-D/3-D)
- Under compression of the hot spot

TC13126

Increase of the residual kinetic energy in asymmetric implosions results in under-compression of the hot spot

Simulated energy balance* in shot 77066



$E_{kin}^{shell} = 1.19$ kJ

E_{kin}^{res} (1-D) = 0.07 kJ (6%)

E_{kin}^{res} (3-D) = 0.22 kJ (18%)

$\Delta E_{kin}^{res} \approx 0.15$ kJ (12%)

TC13127

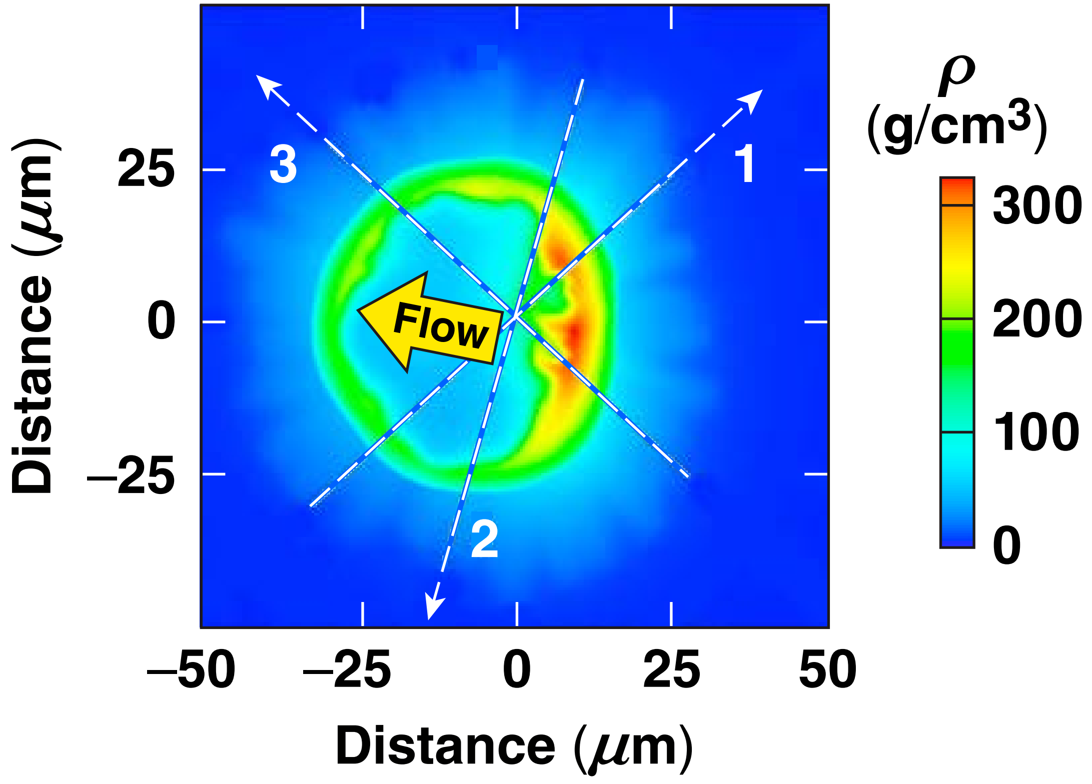
---

*Energies are integrated over the center volume of $R = 200\ \mu m$

Simulations of shot 77066 reproduce the magnitude of asymmetric plasma flow in the hot spot but not directionality

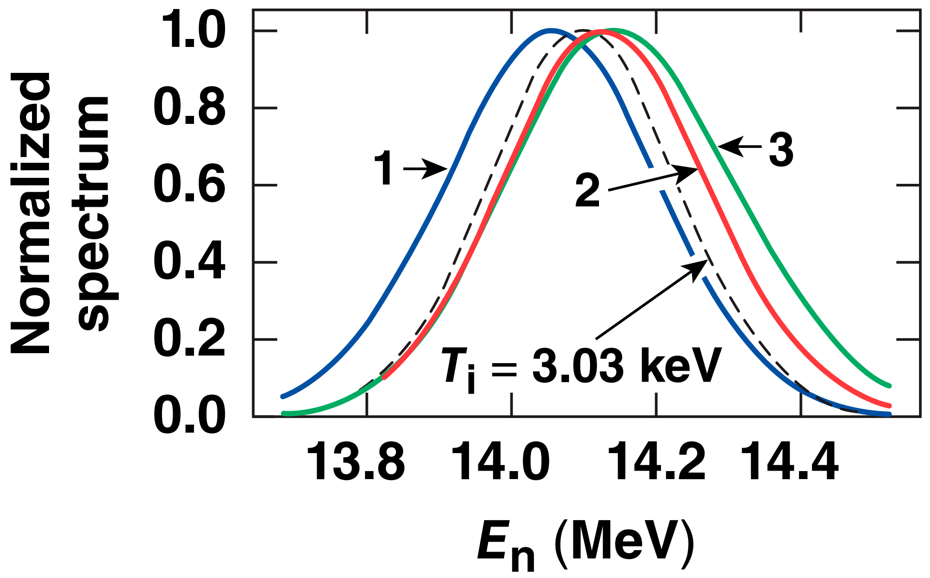
Target at peak neutron production, t = 2.66 ns

Equatorial cut (θ = 90°)



- **Diagnostic is being developed to measure on-target drive asymmetries**

Simulated DT-neutron spectra



Inferred $\langle T_i \rangle_n$ (keV)

Direction	Experiment	Simulations
1 (θ = 85°)	3.6±0.2	3.9
2 (θ = 88°)	3.8±0.2	3.5
3 (θ = 61°)	3.2±0.2	4.4

$\Delta T_i \approx 0.6$ keV $\Delta T_i = 0.9$ keV

Outline

- Introduction
- Measured evidences of large-scale asymmetries
- 3-D hydrodynamic codes at LLE
- *ASTER* simulations of drive asymmetry in room-temperature OMEGA implosions
- Simulations of a cryogenic OMEGA implosion
- **Path forward**

Open Questions

A better understanding of the role of large-scale asymmetries in OMEGA implosions is required

- Are large-scale modes the only source of target degradation for mid- and high-adiabat implosions?
  - 1-D physics
  - small-scale mix
- What is the main source for large-scale modes?
  - ice/ablator-shell asymmetry
  - uncertainty in beam balance/pointing/timing
  - uncertainty in target positioning
- Can we better measure actual laser nonuniformities on a target?

Engineering advancements and physics campaigns are planned to improve implosion performance on OMEGA

Target quality

- fill-tube cryogenic system for nonpermeable ablators
- clean environment
- polystyrene shells

Illumination uniformity

- reconstruction and correction of in-flight shell shapes
- campaign for measuring and improving beam balance
- individual beam-profile measurements

Coupling

- R75 design*
- 61st-beam project with a tunable λ**
- tricolor OMEGA upgrade

1-D physics

- 1-D cryo campaign***
- shell release†
- shell thickness‡
- CH/DT interface
- shock timing
- conduction zone††

---

*V. N. Goncharov *et al.*,TO5.00003, this conference.

**D. H. Froula *et al.*, UO9.00008, this conference.

***R. Betti *et al.*, PO5.00008, this conference.

†J. P. Knauer *et al.*, NO5.00008, this conference.

‡D. T. Michel *et al.*, TO5.00006, this conference.

††A. K. Davis *et al.*, NO8.00007, this conference.

Summary/Conclusions

Consistent interpretation of OMEGA direct-drive implosions indicates significant effects of large-scale asymmetries

- Several x-ray and neutron-based observations show the presence of large-scale asymmetries in direct-drive cryogenic and room-temperature OMEGA implosions
- Three-dimensional *ASTER** simulations using measured low-ℓ-mode seeds reproduce these observations
- Simulations indicate that asymmetries resulting from measured target offset, beam-to-beam power imbalance, and ice-shell nonuniformities reduce the stagnation pressure by 40%

Three-dimensional simulations are essential to guide physics campaigns and engineering advancements on the OMEGA laser.

---

*I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).