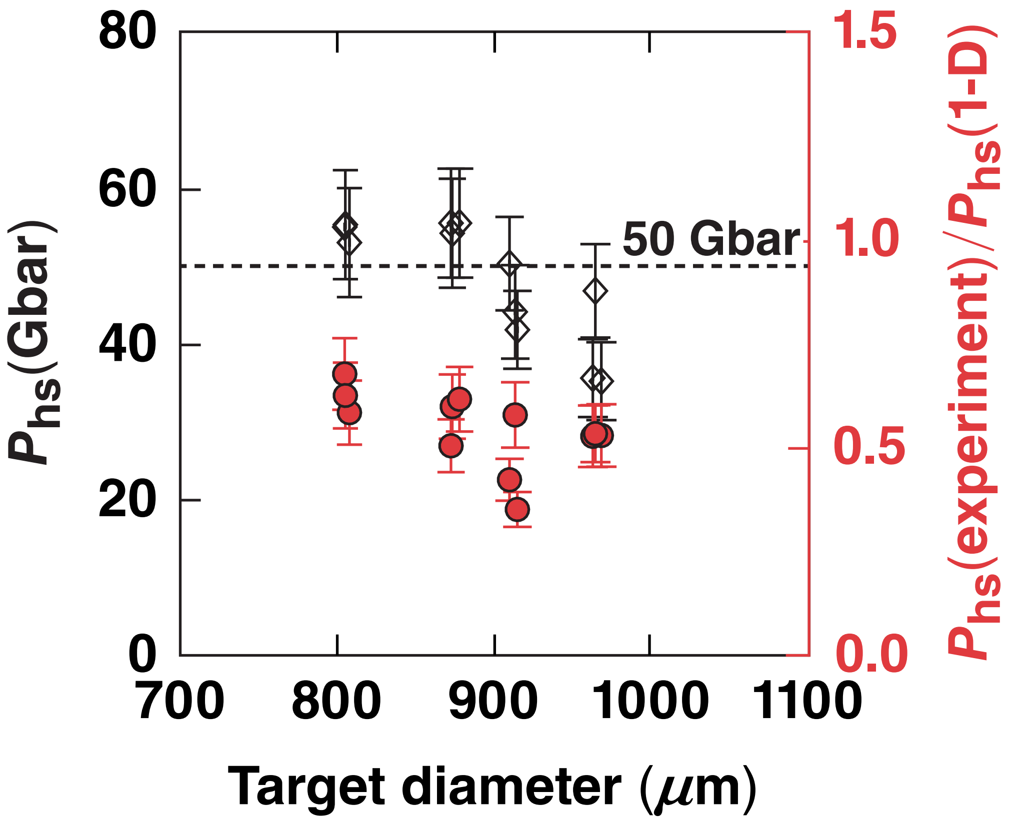
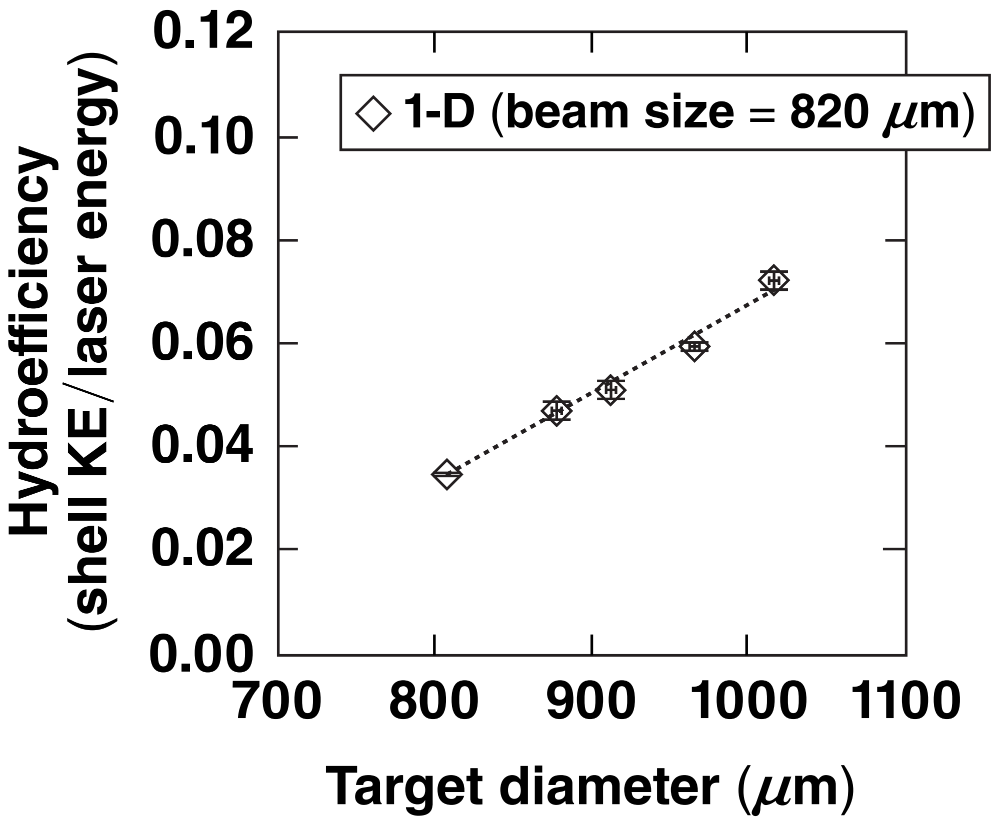
Energy Coupling and Hot-Spot Pressure in Direct-Drive Layered DT Implosions on OMEGA





S. P. Regan
University of Rochester
Laboratory for Laser Energetics

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A 50-Gbar hot-spot pressure and an increase in hydroefficiency have been demonstrated on OMEGA

- A hot-spot pressure of $P_{\mathrm{hs}} = 56 \pm 7$ Gbar was inferred from x-ray and nuclear diagnostics in direct-drive layered DT implosions on OMEGA
- Cross-beam energy transfer* (CBET) was reduced by increasing the initial target diameter while keeping the laser beam size constant
  - as $R_{\mathrm{beam}}/R_{\mathrm{target}}$ was varied from 1.0 to 0.8, the hydroefficiency increased by ~40% because of CBET reduction
- Low-mode distortion of the hot spot causes early truncation of the neutron rate and lower P_{hs}

A path to 100-Gbar hot-spot pressure on OMEGA and spherical-direct-drive (SDD) at the National Ignition Facility (NIF) is being developed.

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* I. V. Igumenshchev *et al.*, Phys. Plasmas 17, 122708 (2010);
D. H. Froula *et al.*, Phys. Rev. Lett. 108, 125003 (2012);
V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

Collaborators

V. N. Goncharov, T. C. Sangster, R. Betti, T. R. Boehly, M. J. Bonino, E. M. Campbell,
D. Cao, T. J. B. Collins, R. S. Craxton, A. K. Davis, J. A. Delettrez, D. H. Edgell, R. Epstein,
C. J. Forrest, D. H. Froula, V. Yu. Glebov, D. R. Harding, M. Hohenberger, S. X. Hu,
I. V. Igumenshchev, R. T. Janezic, J. H. Kelly, T. J. Kessler, J. P. Knauer, T. Z. Kosc,
J. A. Marozas, F. J. Marshall, R. L. McCrory, P. W. McKenty, D. T. Michel, J. F. Myatt,
P. B. Radha, M. J. Rosenberg, W. Seka, W. T. Shmayda, A. Shvydky, S. Skupsky,
A. A. Solodov, C. Stoeckl, W. Theobald, M. D. Wittman, B. Yaakobi, and J. D. Zuegel

University of Rochester
Laboratory for Laser Energetics

J. A. Frenje, M. Gatu Johnson, R. D. Petrasso

Massachusetts Institute of Technology

S. P. Obenschain, M. Karasik, and A. J. Schmitt

Naval Research Laboratory

D. D. Meyerhofer and M. J. Schmitt

Los Alamos National Laboratory

Outline

- 50-Gbar hot-spot pressure
- CBET reduction
- Effect of low-mode distortions on hot-spot pressure
- Path to 100 Gbar on OMEGA and direct drive on the NIF

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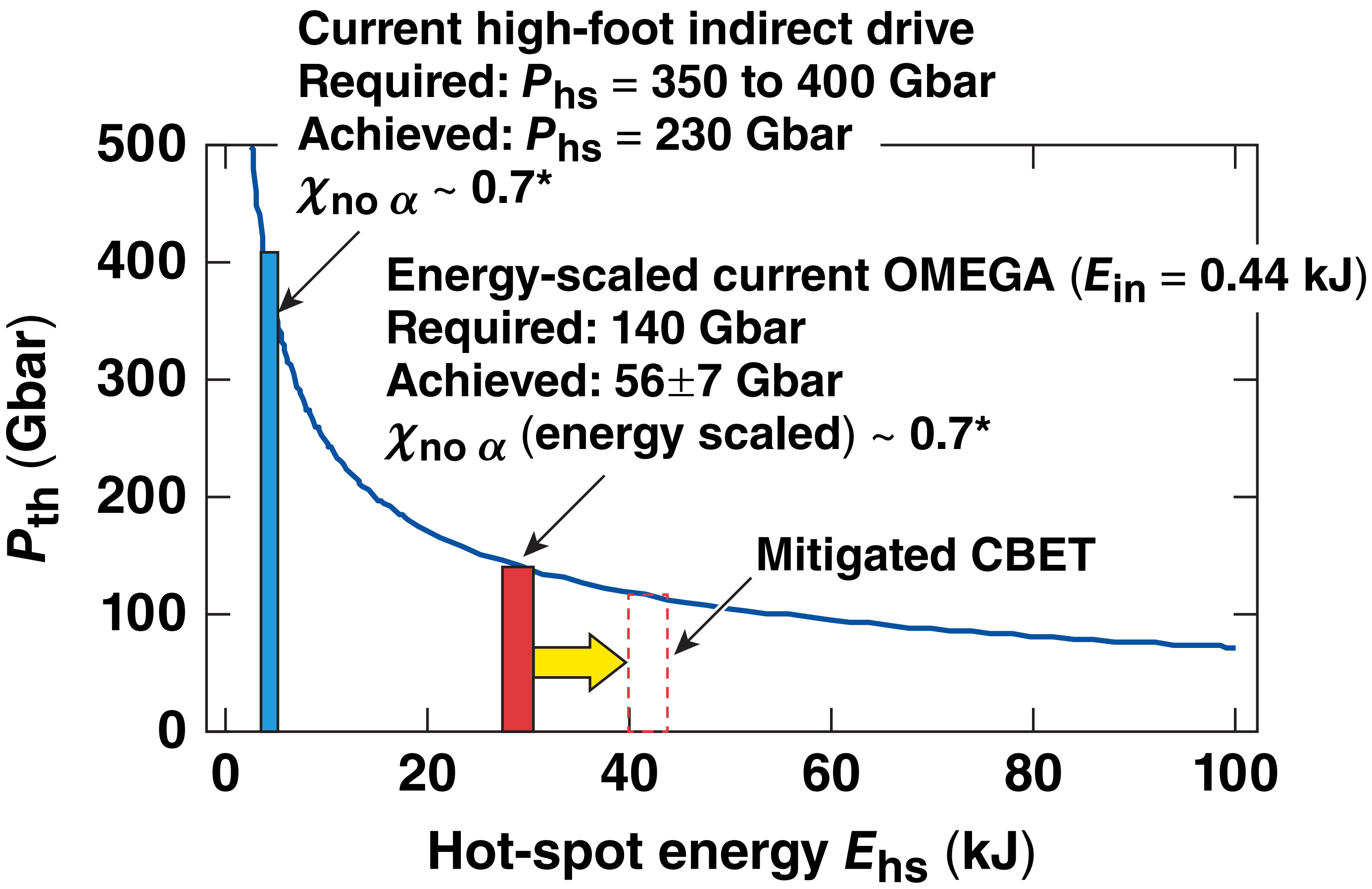
The hot-spot pressure and convergence ratio required for ignition decreases with increasing energy coupled to the hot spot



Current high-foot indirect drive
Required: P_{hs} = 350 to 400 Gbar
Achieved: P_{hs} = 230 Gbar
$\chi_{\text{no }\alpha} \sim 0.7$*

Energy-scaled current OMEGA (E_{in} = 0.44 kJ)
Required: 140 Gbar
Achieved: 56±7 Gbar
$\chi_{\text{no }\alpha}$ (energy scaled) ~ 0.7*

Mitigated CBET

- Pressure threshold for ignition

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

- Generalized Lawson criterion**

$$\chi = P\tau/P\tau_{ign} = (\rho R)^{0.61}\,(0.24\,Y^{16}/M)^{0.34}$$

$$\chi_{OMEGA} \rightarrow \chi_{NIF} \sim E^{0.37}$$

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

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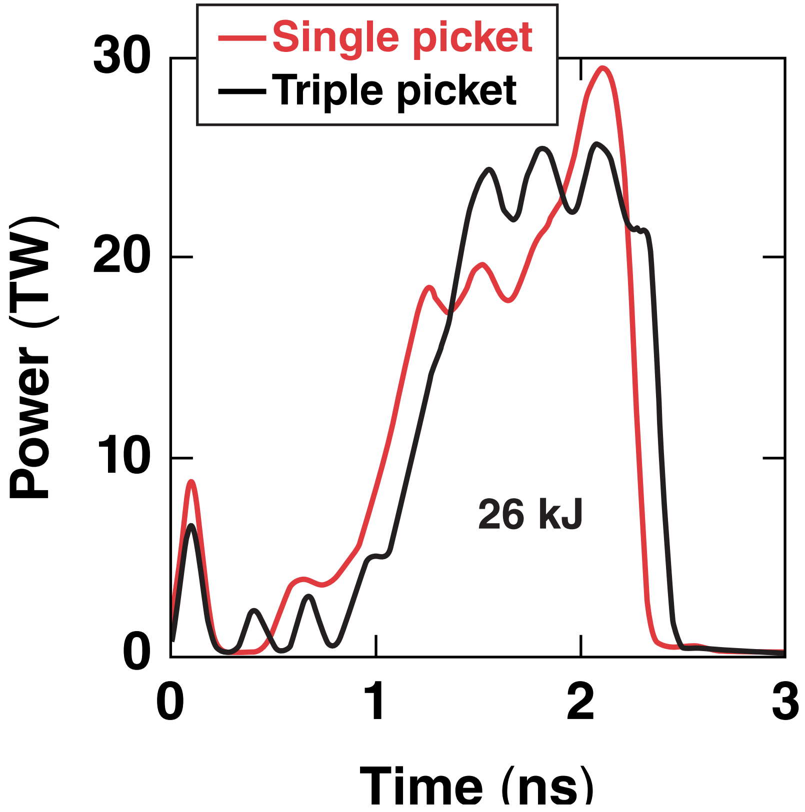
* R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015);
A. R. Christopherson, CI3.00006, this conference (invited).
** R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).
† CR: convergence ratio

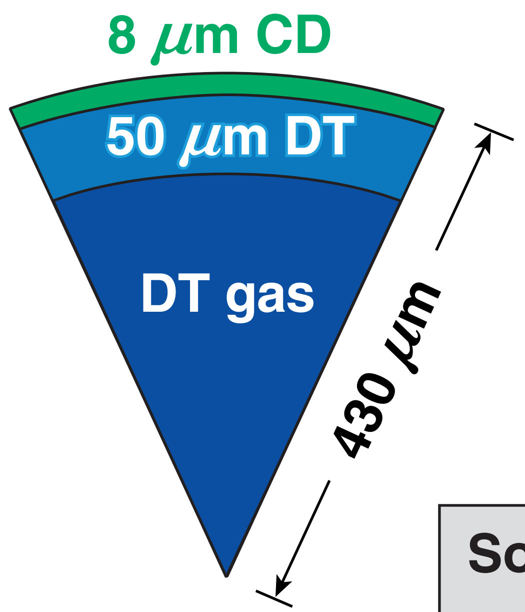
TC12311g

Layered DT targets were imploded on OMEGA for the 50-Gbar campaign*

Laser drive



Target



Target-design parameters

$V_{\text{imp}} = 3.6$ to 3.8×10^7 cm/s
$\alpha = 2.5$ to 4.5
CR = 20 to 23
IFAR** = 15 to 25

$\alpha = P/P_F$
IFAR = shell radius/shell thickness

Sources of low-mode drive nonuniformity

1. Laser beam power imbalance (15% to 20%)
2. Target offset (5 to 30 μm)
3. Laser beam mispointing (10-μm rms)

OMEGA layered DT implosions are hydrodynamically scaled from the NIF direct-drive–ignition design.

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*V. N. Goncharov *et al.*, UO4.00005, this conference.
**IFAR: in-flight aspect ratio

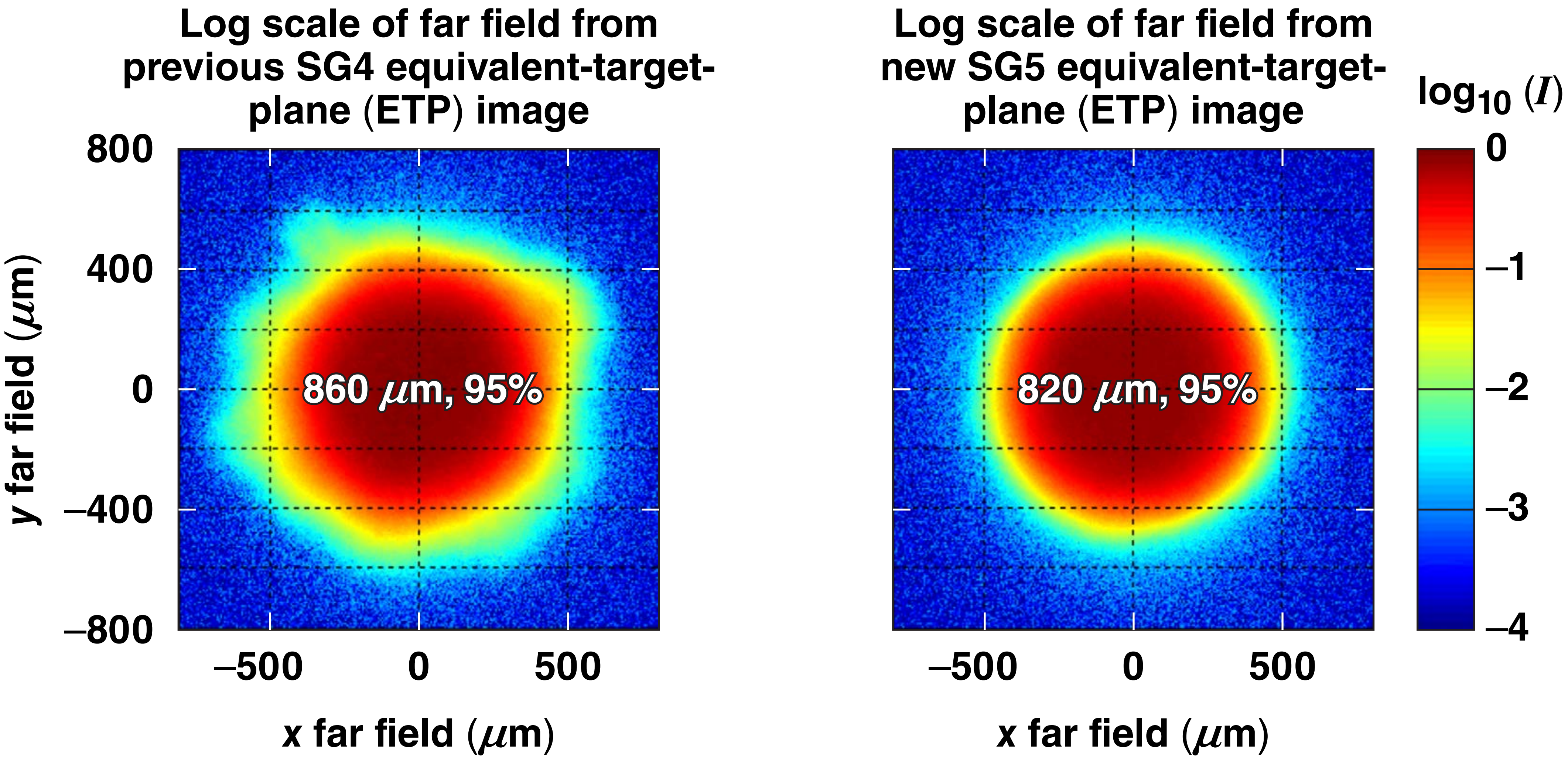
TC12314c

Improvements to the laser, target, and diagnostics were required to increase P_{hs} on OMEGA

- Laser
  - SG5 phase plates (820 μm diameter, 95% energy encircled)
  - multipulse driver [more energy on target, apply smoothing by spectral dispersion (SSD) to pickets only]
- Target—Isotope Separator System
  - D:T is 50:50 at the inner ice layer and gas vapor with <0.1% H
- Diagnostics
  - high-temporal (30-ps) and spatial-resolution (6-μm) Kirkpatrick–Baez microscope (KBframed)
  - neutron temporal diagnostic with 40-ps temporal response (P11NTD)

A new set of phase plates designed to improve the on-target drive uniformity were developed for this campaign

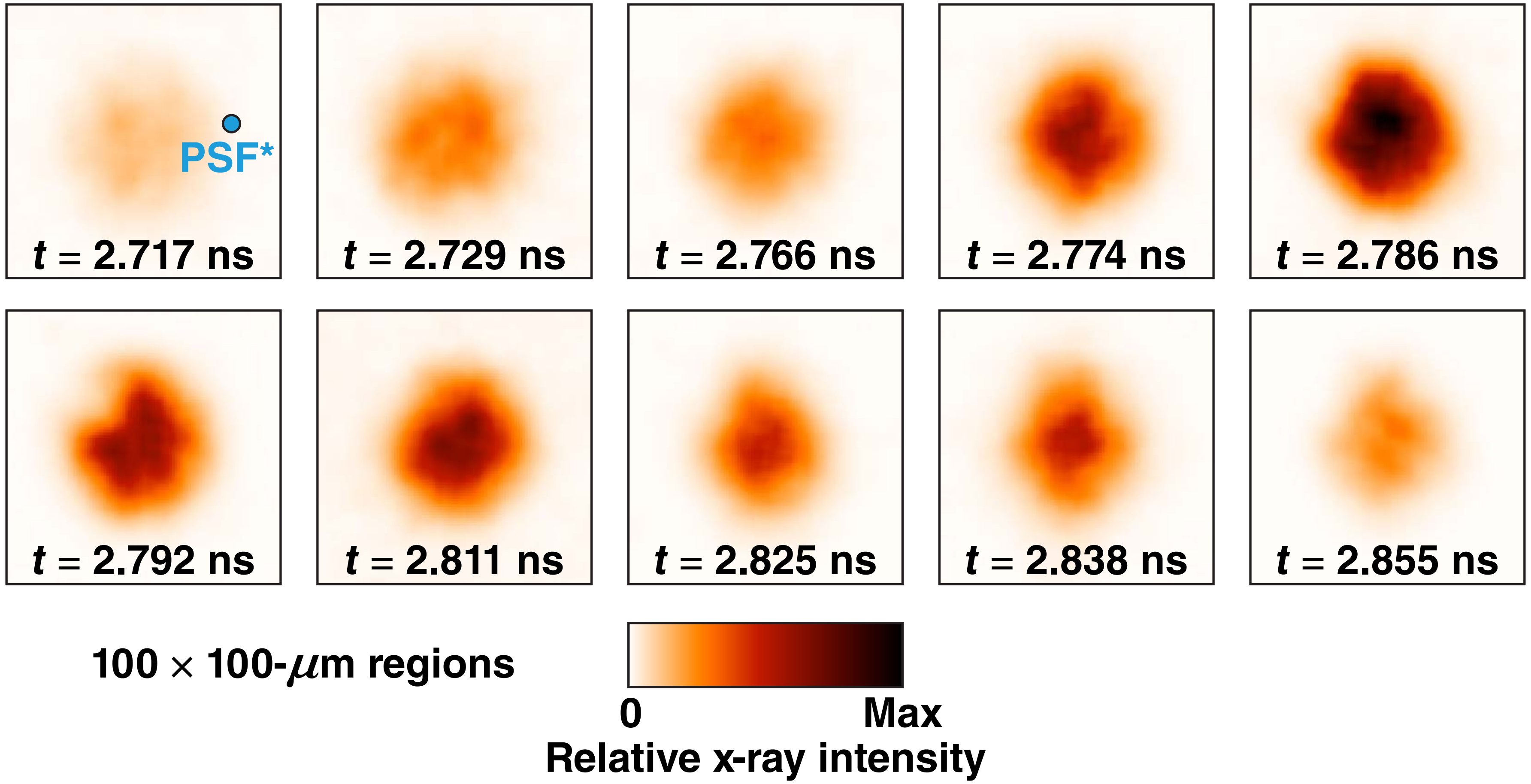
$$I \sim \mathbf{exp}\left[\left(-r/r_0\right)^n\right]$$



E23691d

The 16-channel, gated, Kirkpatrick–Baez microscope (KBframed) measures the evolution of the hot-spot size around stagnation

OMEGA cryogenic DT target implosion, shot 76828

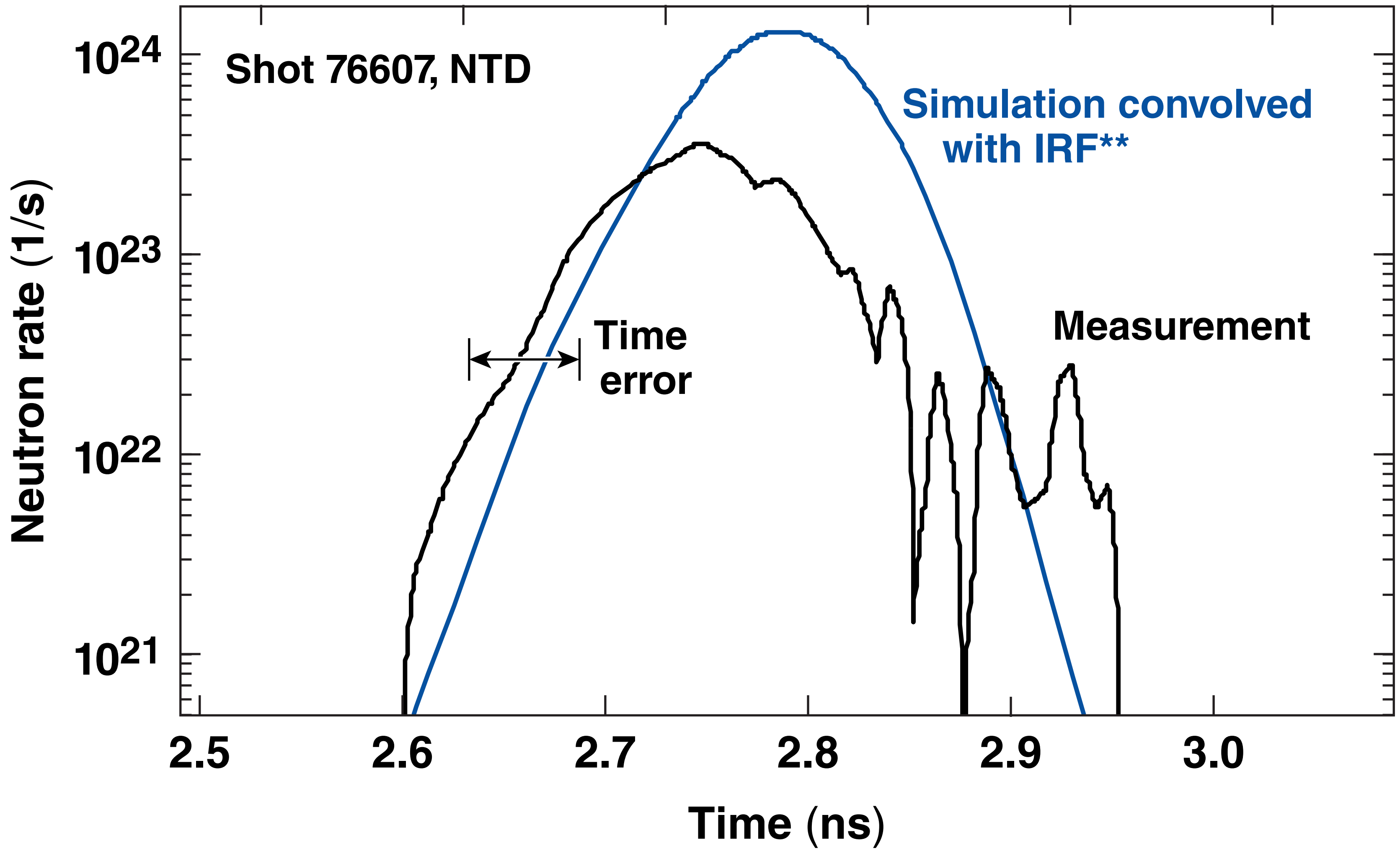


KBframed has 30-ps temporal resolution and 6-μm spatial resolution, and records an image every 15 ps in the 4- to 8-keV photon-energy range.

F. J. Marshall *et al.*, UO4.00004, this conference; F. J. Marshall, Rev. Sci. Instrum. 83, 10E518 (2012).

*PSF: point spread function

The neutron rate is recorded with the neutron temporal diagnostic (NTD*)



P11NTD can measure a minimum burnwidth of 50 ps with a 10% accuracy and absolute bang time ±25 ps (signal-to-background is ~100).

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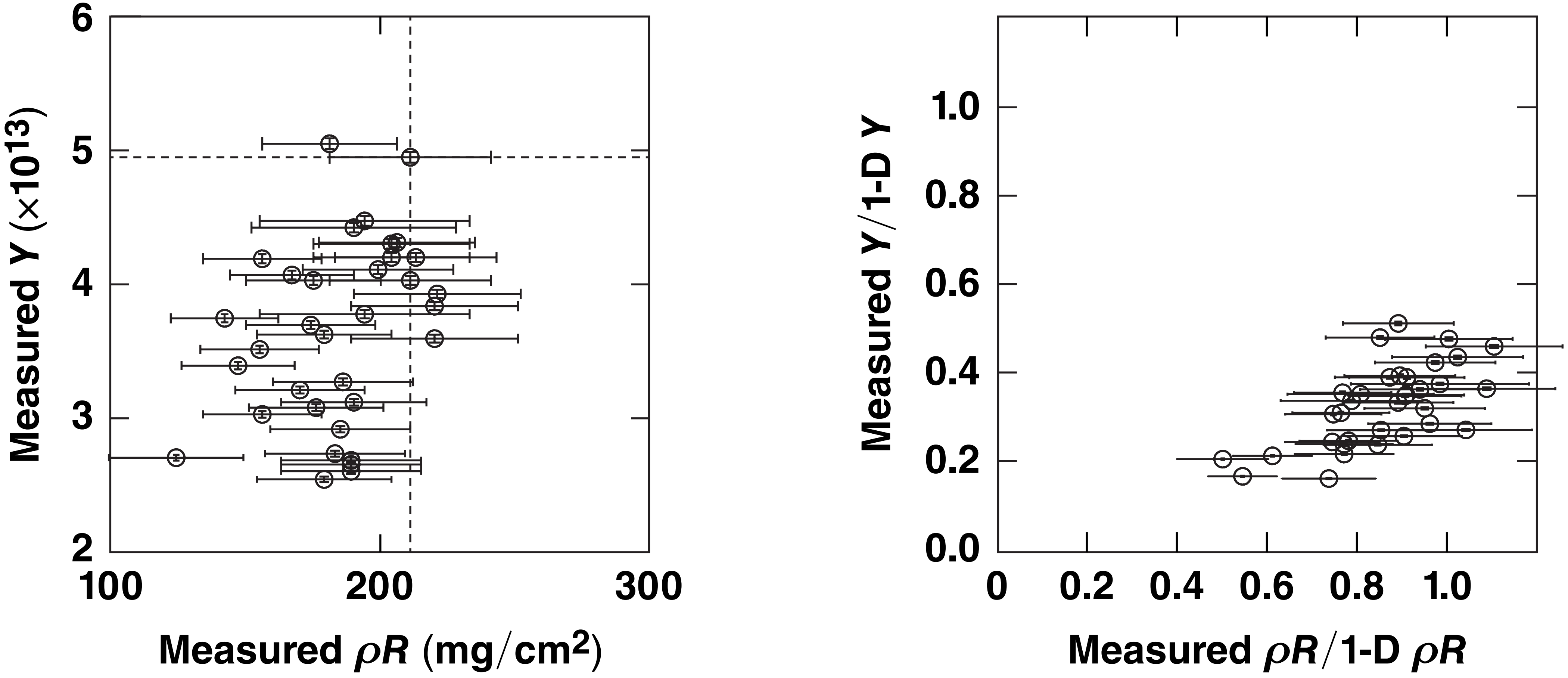
*C. Stoeckl *et al.*, "A Neutron Temporal Diagnostic for High-Yield DT Cryogenic Implosions on OMEGA," to be submitted to the Review of Scientific Instruments.

**IRF: instrument response function

TC12365c

A primary DT neutron yield up to ~5 × 10^{13} with a ρR of ~200 mg/cm^2 has been recorded



Yield-over-clean (YOC) ≡ measured Y/1-D Y = 0.2 to 0.6

ρROC ≡ measured ρR/1-D ρR = 0.5 to 1

T_i = 2.7 to 3.8 keV

E24749

A hot-spot pressure of 56±7 Gbar was inferred from nuclear and x-ray diagnostics assuming isobaric hot spot*

$$N_{\max} = n_T n_D T^2 \int_{V_{hs}} dV \langle \sigma v \rangle / T^2$$

$$N_{\max} = 2Y \sqrt{\ln 2 / \pi} / \Delta t_{burn}$$

(assuming a Gaussian neutron rate with FWHM** = Δt_{burn})

$$P_{hs} \simeq \left[8Y \sqrt{\ln 2 / \pi} \Big/ \left(\Delta t_{burn} \int_{V_{hs}} dV \langle \sigma v \rangle / T^2 \right) \right]^{1/2}$$

OMEGA cryogenic target shot 77066

R_{17} = 22.0±0.4 μm (KBframed + framed pinholes)

$Y = 4.0 \times 10^{13}$

Δt_{burn} = 63±5 ps (x rays), 67±5 ps (neutrons), 66 ps (1-D)

$\langle T_i \rangle_n$ = 3.2±0.4 keV

$P_{hs,\,exp}$ = 56±7 Gbar

$P_{hs,\,1\text{-}D}$ = 90 Gbar

$\alpha = 3.3$

$$T(r) = T_c \left[1 - (r/R_{hs})^2 (1 - 0.15^{3/2}) \right]^{2/3}$$

T_c is the maximum hot-spot temperature

$$\langle T_i \rangle_n = \left(\int_{V_{hs}} dV \langle \sigma v \rangle / T \Big/ \int_{V_{hs}} dV \langle \sigma v \rangle / T^2 \right)$$

$$R_{hs} = 1.06\, R_{17}$$

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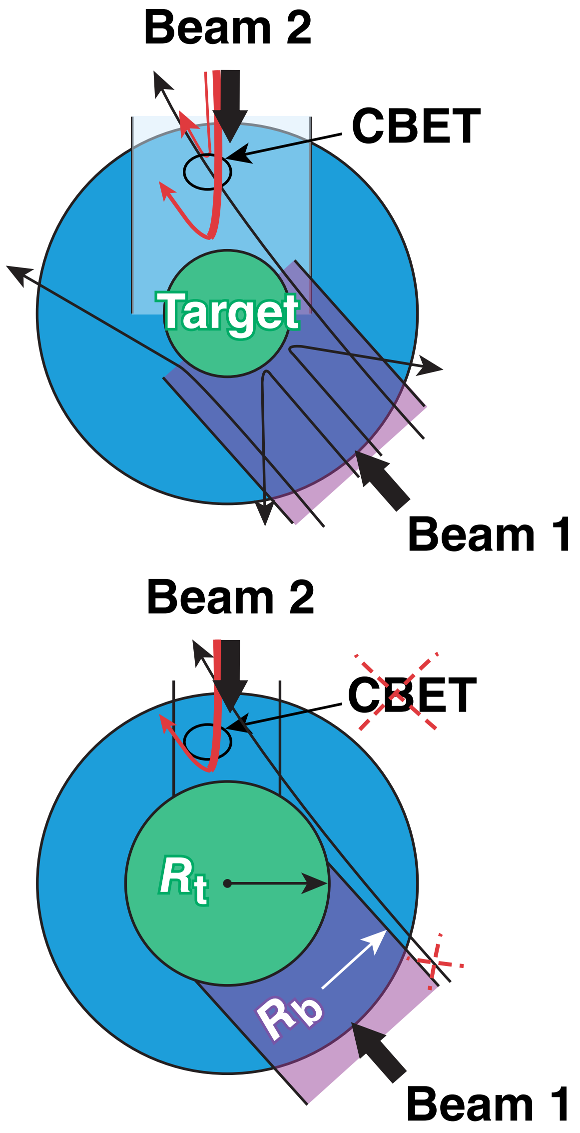
[*] C. Cerjan, P. T. Springer, and S. M. Sepke, Phys. Plasmas 20, 056319 (2013); R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

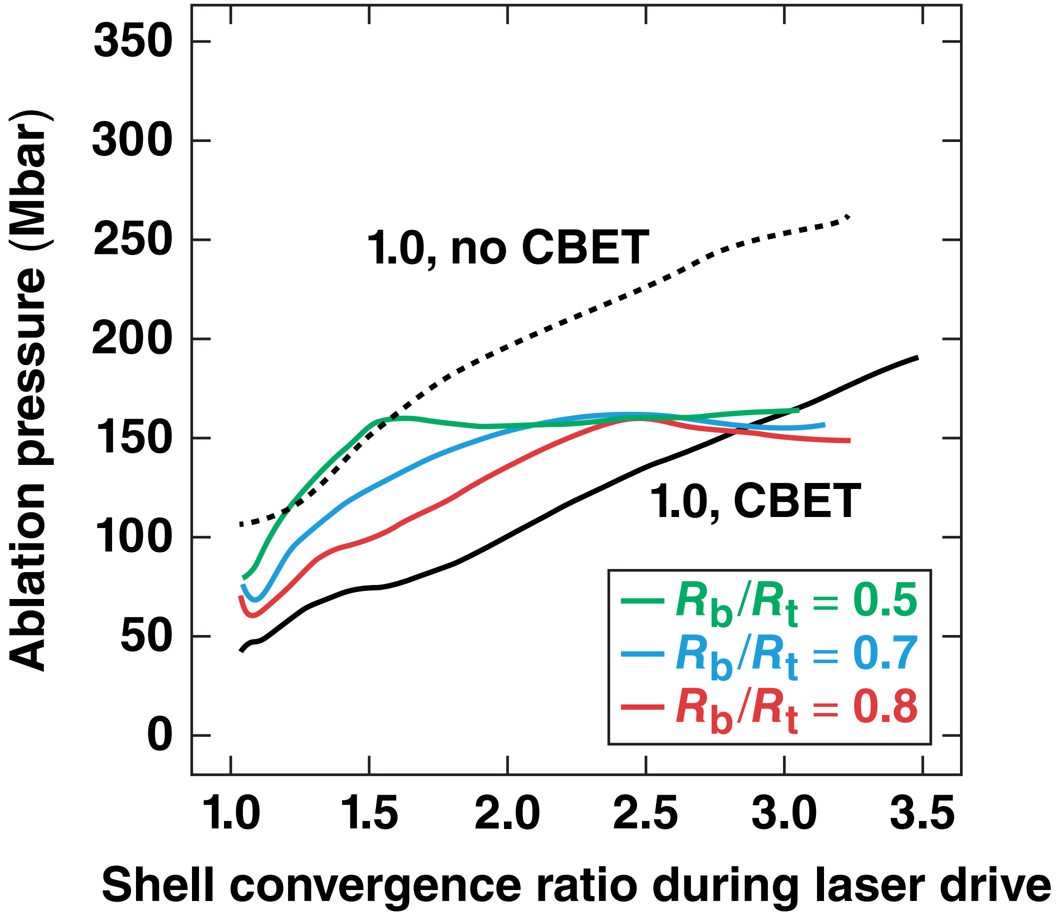
[**] FWHM: full width at half maximum

Outline

- 50-Gbar hot-spot pressure
- **CBET reduction**
- Effect of low-mode distortions on hot-spot pressure
- Path to 100 Gbar on OMEGA and direct drive on the NIF

R_b/R_t was varied from 1.0 to 0.8 by changing the target diameter to reduce CBET*





The target diameter is varied from 800 to 1000 μm, while keeping the laser beam size constant, to reduce CBET.

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*I. V. Igumenshchev *et al.*, Phys. Plasmas 17, 122708 (2010); D. H. Froula *et al.*, Phys. Rev. Lett. 108, 125003 (2012); V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014); V. N. Goncharov *et al.*, UO4.00005, this conference.

TC12317b

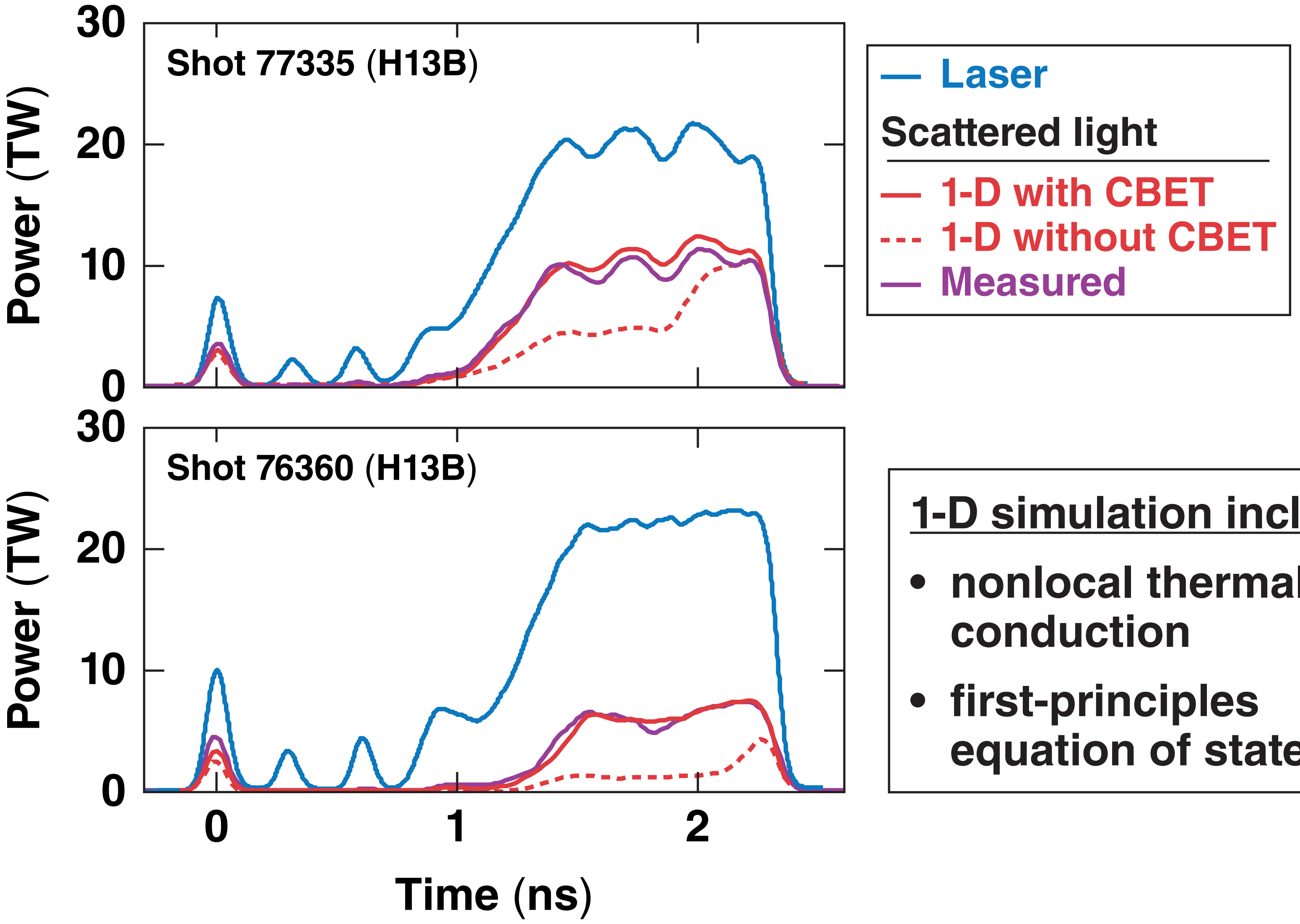
CBET modeling is required in the 1-D simulation to match the measurements*

Outside diameter (OD) = 805 μm
$I = 1.1 \times 10^{15}$ W/cm^2
$f_{\text{abs, expt}} = 54 \pm 6\%$
$f_{\text{abs, 1-D with CBET}} = 52\%$
$f_{\text{abs, 1-D without CBET}} = 71\%$

- Absorption reduced 27% by CBET

OD = 1017 μm
$I = 0.7 \times 10^{15}$ W/cm^2
$f_{\text{abs, expt}} = 75 \pm 2\%$
$f_{\text{abs, 1-D with CBET}} = 77\%$
$f_{\text{abs, 1-D without CBET}} = 92\%$

- Absorption reduced 16% by CBET



1-D simulation includes*

- nonlocal thermal conduction
- first-principles equation of state**

The effect of CBET is reduced for the larger target.

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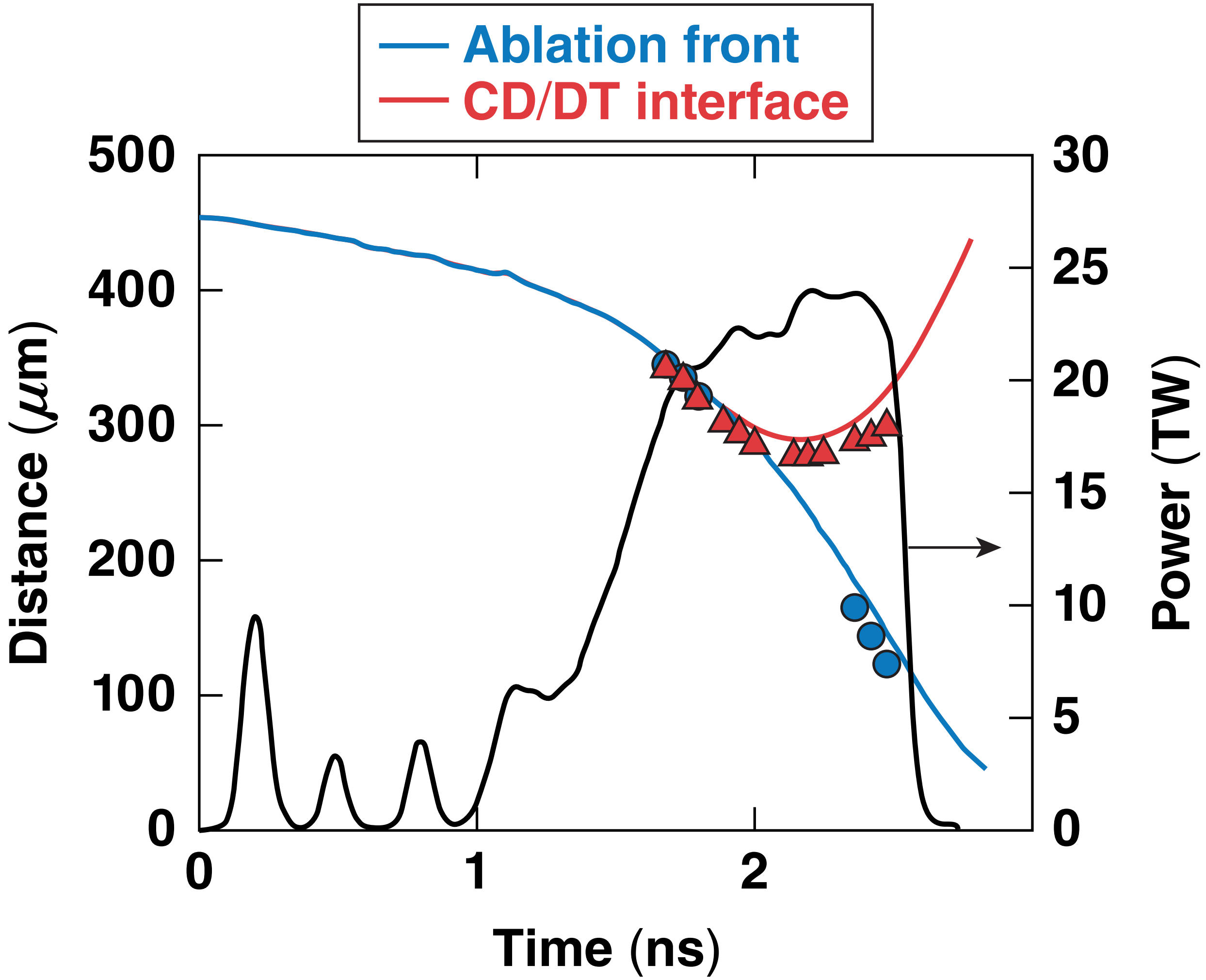
* V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).
** S. X. Hu *et al.*, Phys. Rev. E 92, 043104 (2015).

E24763

CBET modeling is required in the 1-D simulation to match the measurements*

Shot 76607, self-emission imaging**



The measured shell trajectory constrains the model during the acceleration phase.

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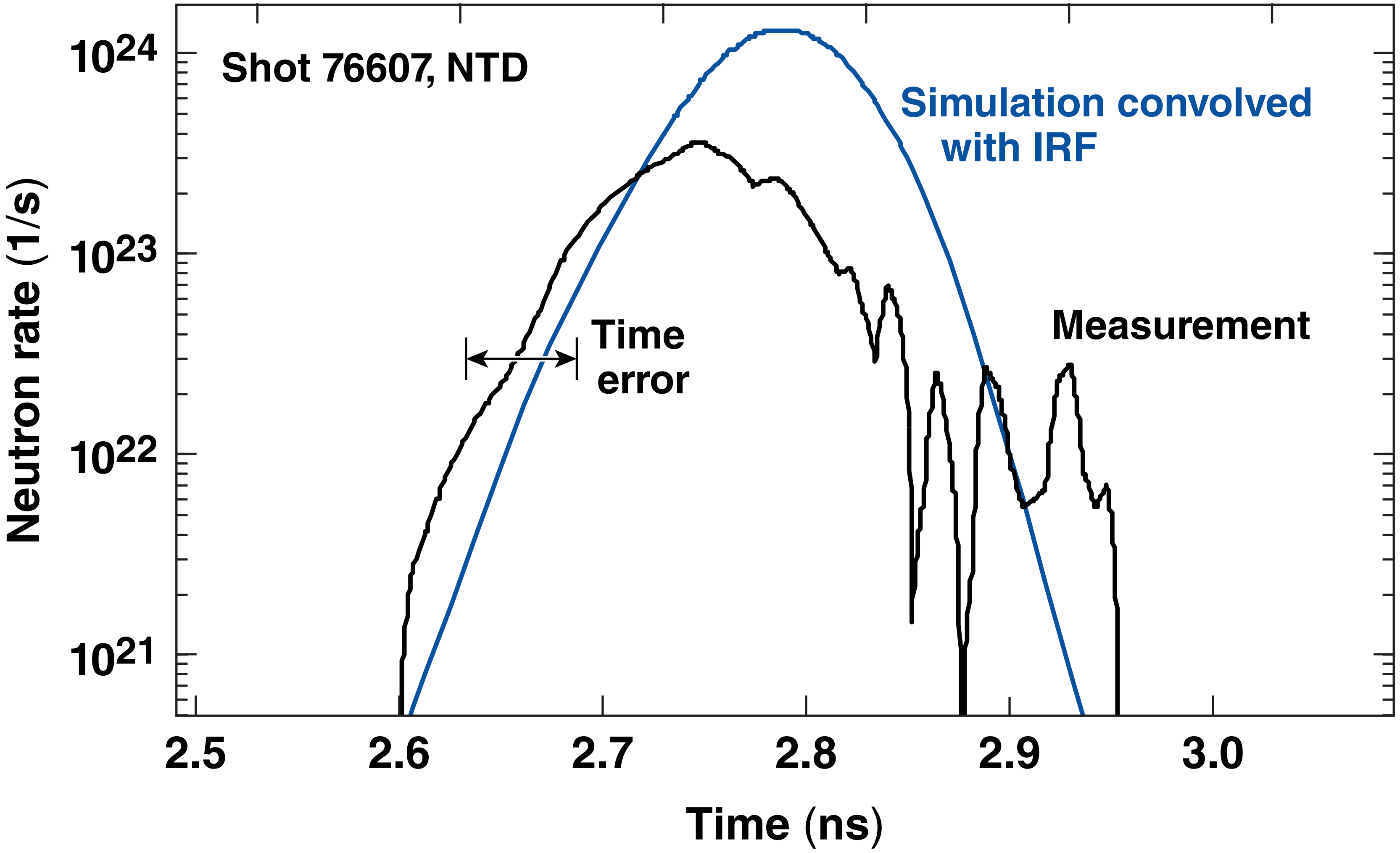
* V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

** D. T. Michel *et al.*, Phys. Rev. Lett. 114, 155002 (2015).

TC12365e

CBET modeling is required in the 1-D simulation to match the measurements*



The measured neutron rate shows deviation from the 1-D prediction near stagnation.

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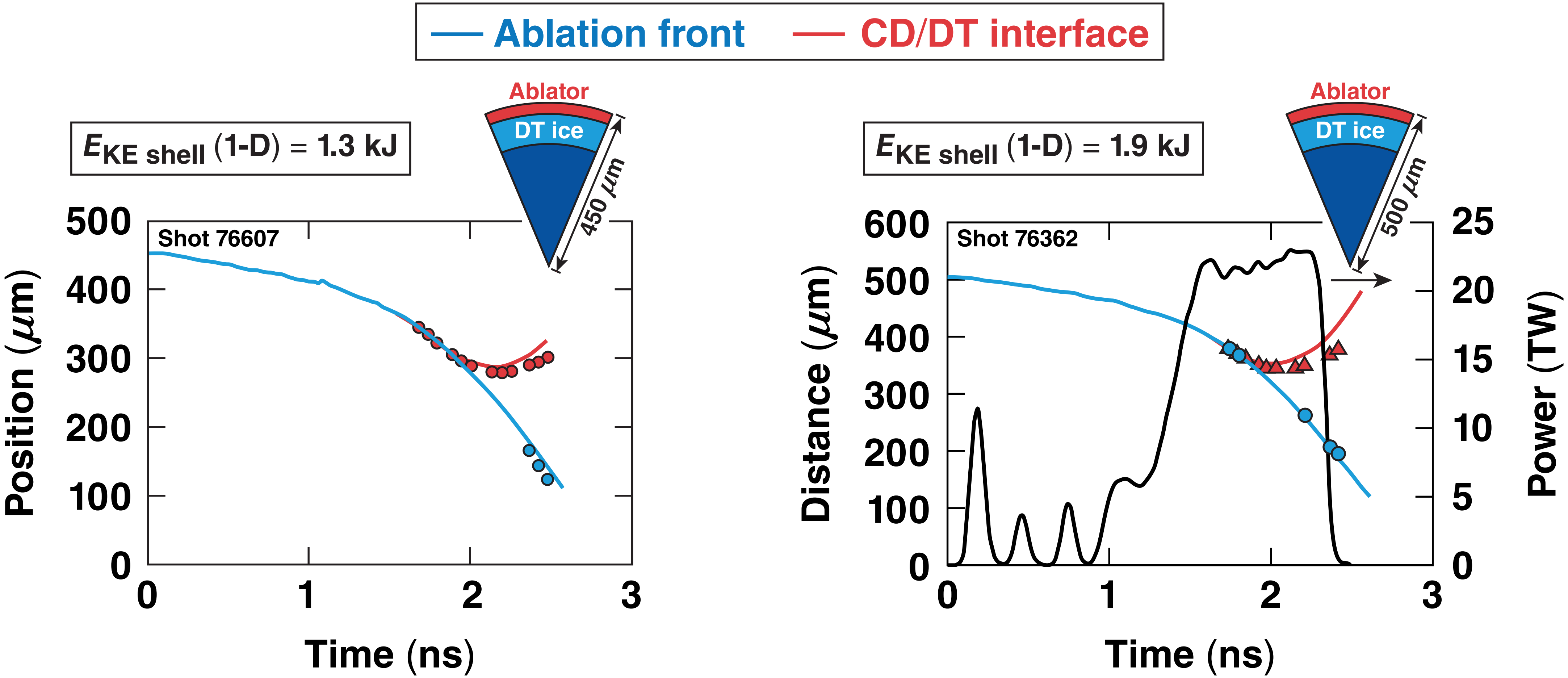
* V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

TC12365d

More kinetic energy is coupled to the larger target because of a reduction in CBET

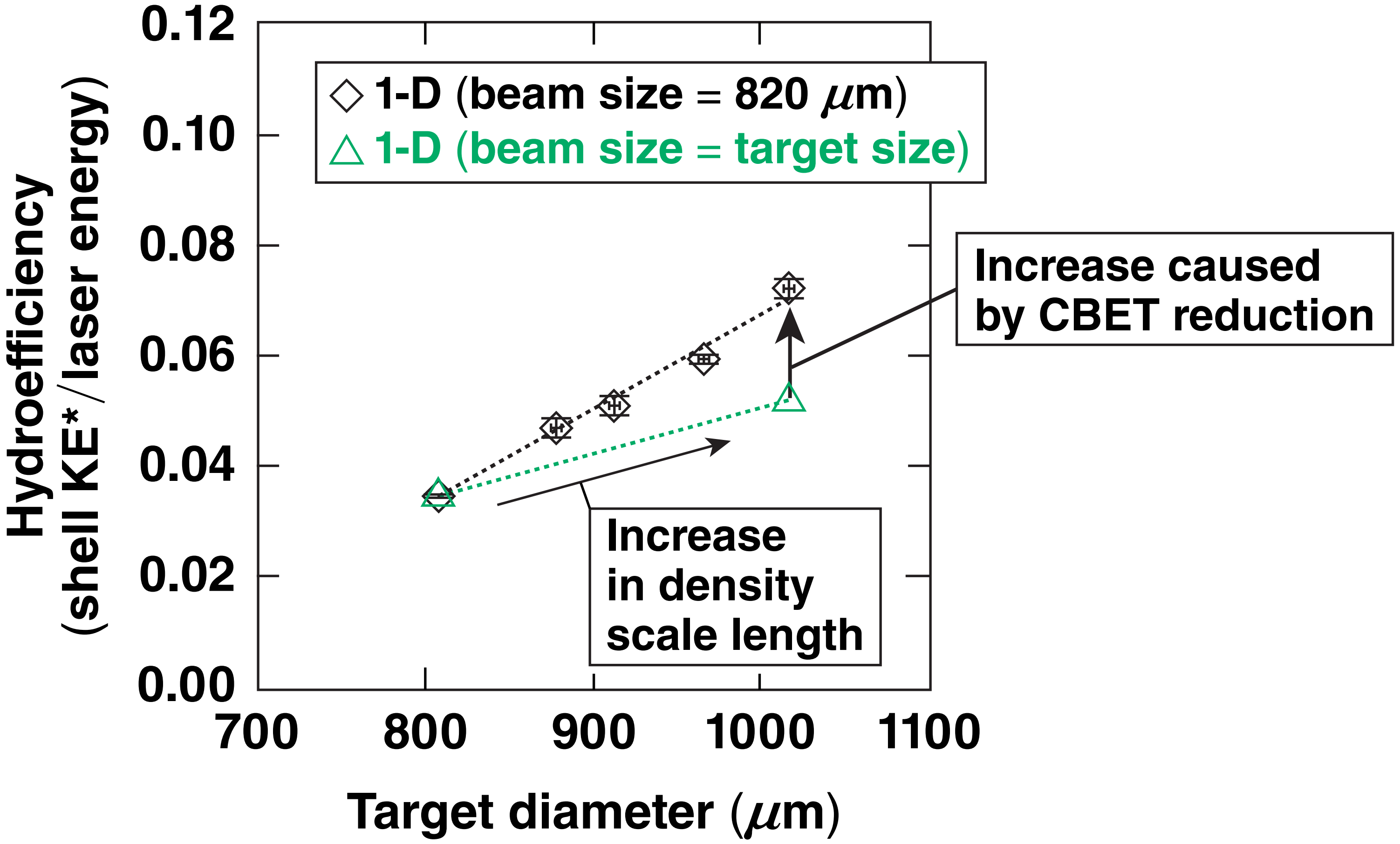
$V_{\text{imp, 1-D}} = 3.6 \times 10^7$ cm/s for both designs



1-D simulations agree with the measured shell trajectories; energy coupling to the imploding shell is taken from the 1-D simulation.

E24015d

An ~40% increase in the hydrodynamic efficiency was inferred because of a reduction in CBET



Measured shell trajectories for 860-μm, 900-μm, and 1000-μm targets with a fixed beam size constrain the 1-D simulations.

E24751

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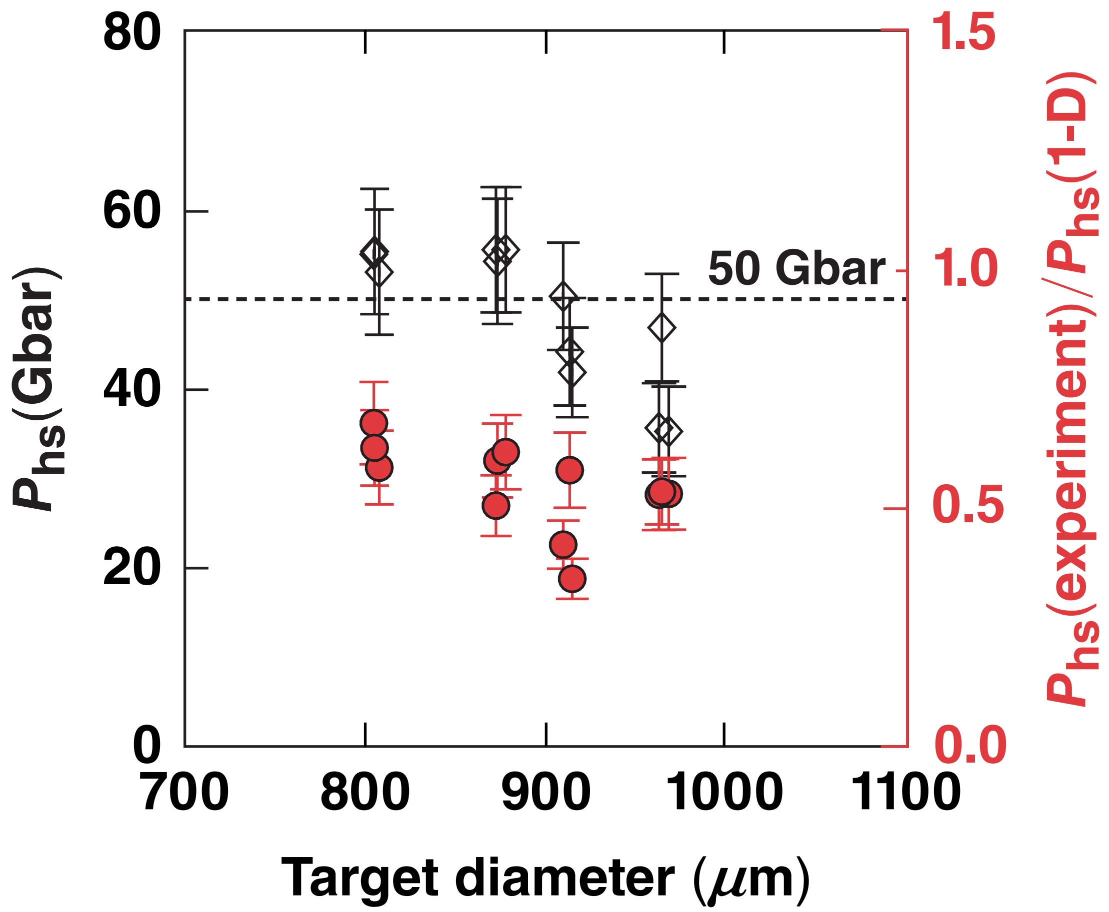
* KE: kinetic energy

The observed increase in energy coupling with target diameter does not result in a higher hot-spot pressure



The peak hot-spot pressure of 56±7 Gbar inferred for the smaller targets corresponds to 50% to 65% of the 1-D prediction.

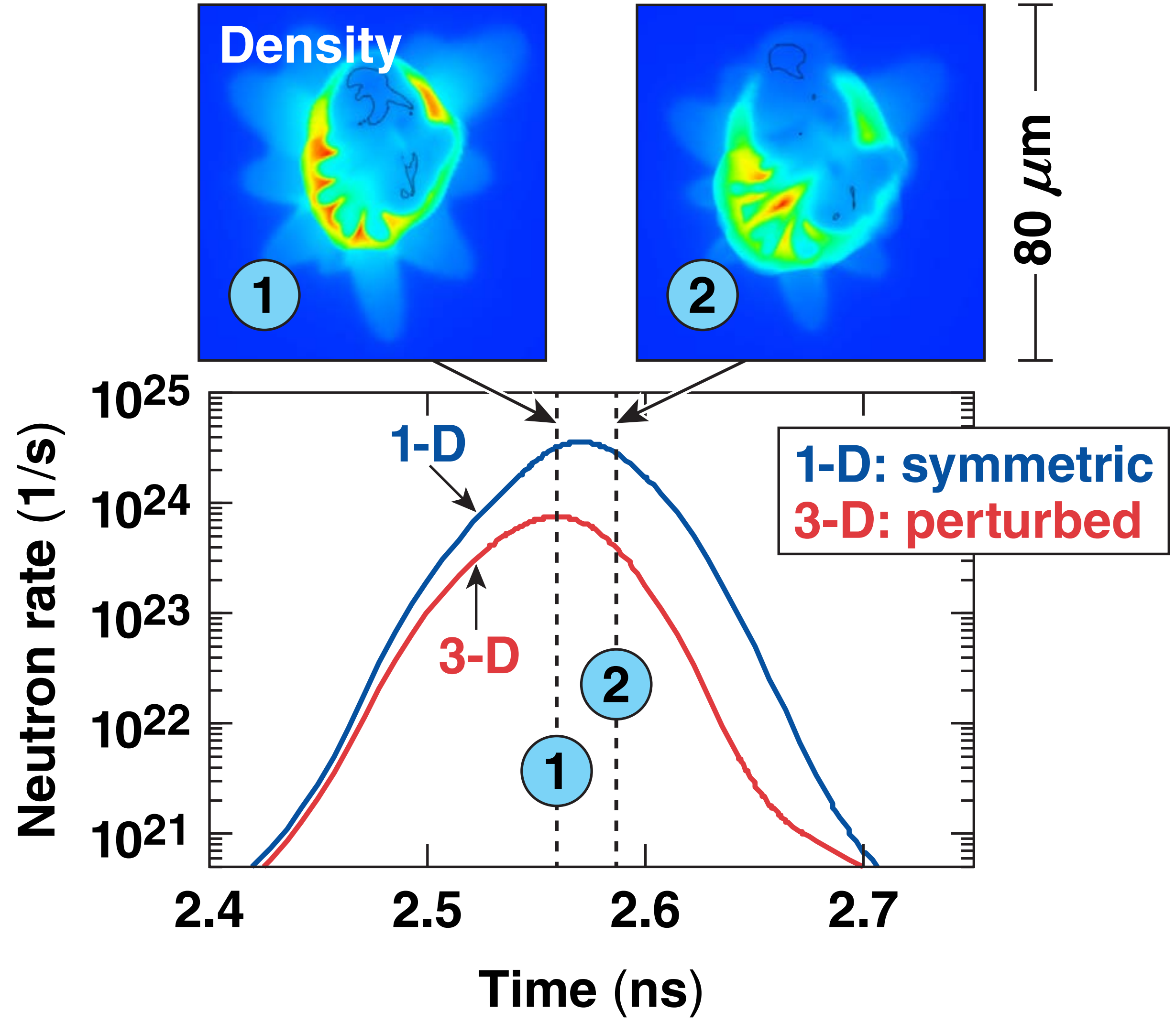
E24751a

Outline

- 50-Gbar hot-spot pressure
- CBET reduction
- **Effect of low-mode distortions on hot-spot pressure**
- Path to 100 Gbar on OMEGA and direct drive on the NIF

Three-dimensional simulations predict early burn truncation because of low-mode ($\ell \leq 5$) hot-spot distortion growth

3-D *ASTER simulations for a 860-μm OD target**



<u>**Perturbation sources**</u>

- 15% rms laser power imbalance
- 20-μm target offset
- 10-μm rms laser beam mispointing

Larger targets have a higher level of low-mode drive nonuniformity because of reduced beam overlap.

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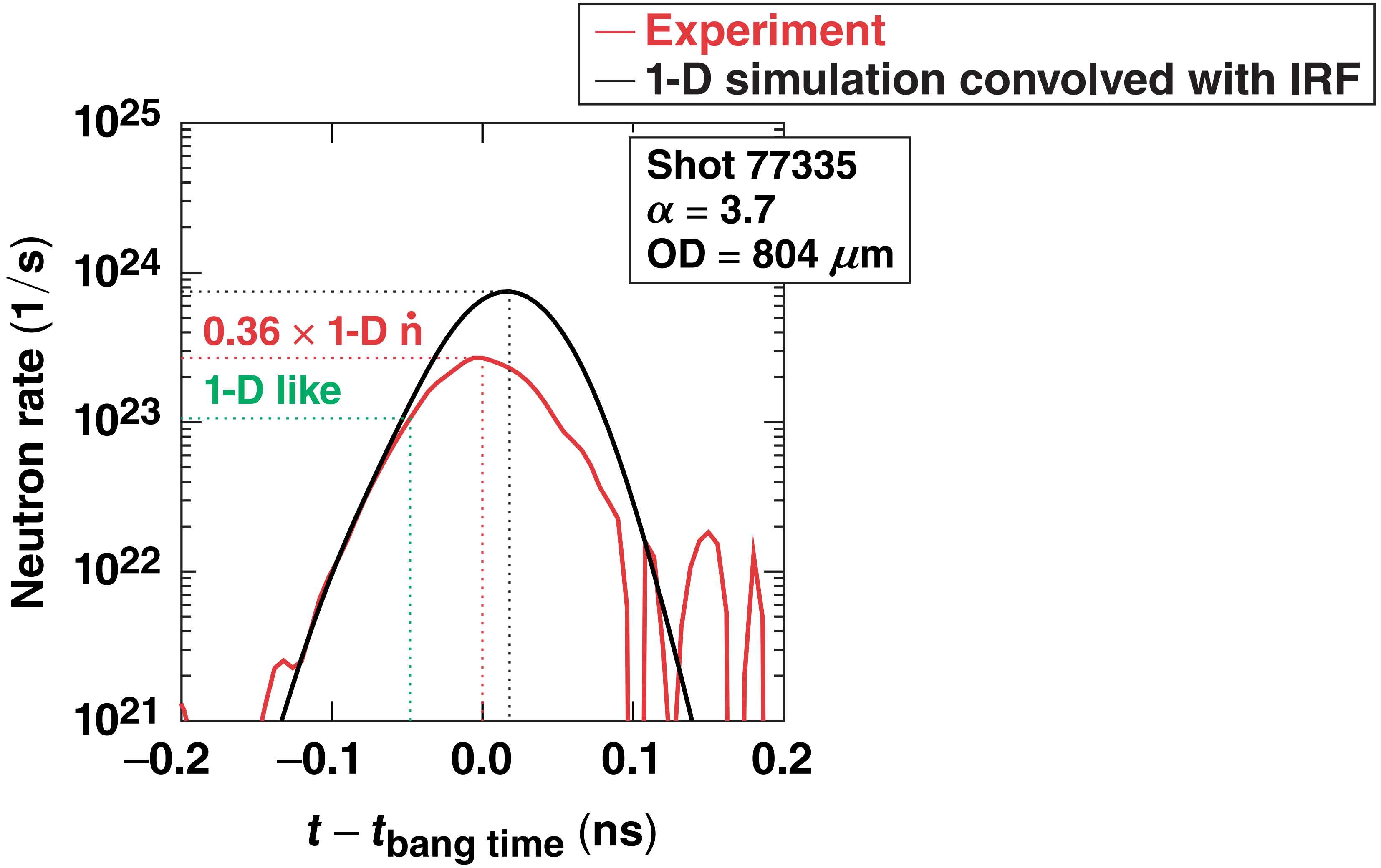
*I. V. Igumenshchev *et al.*, UO4.00015, this conference.

The measured neutron rate shows burn truncation similar to the 3-D simulation

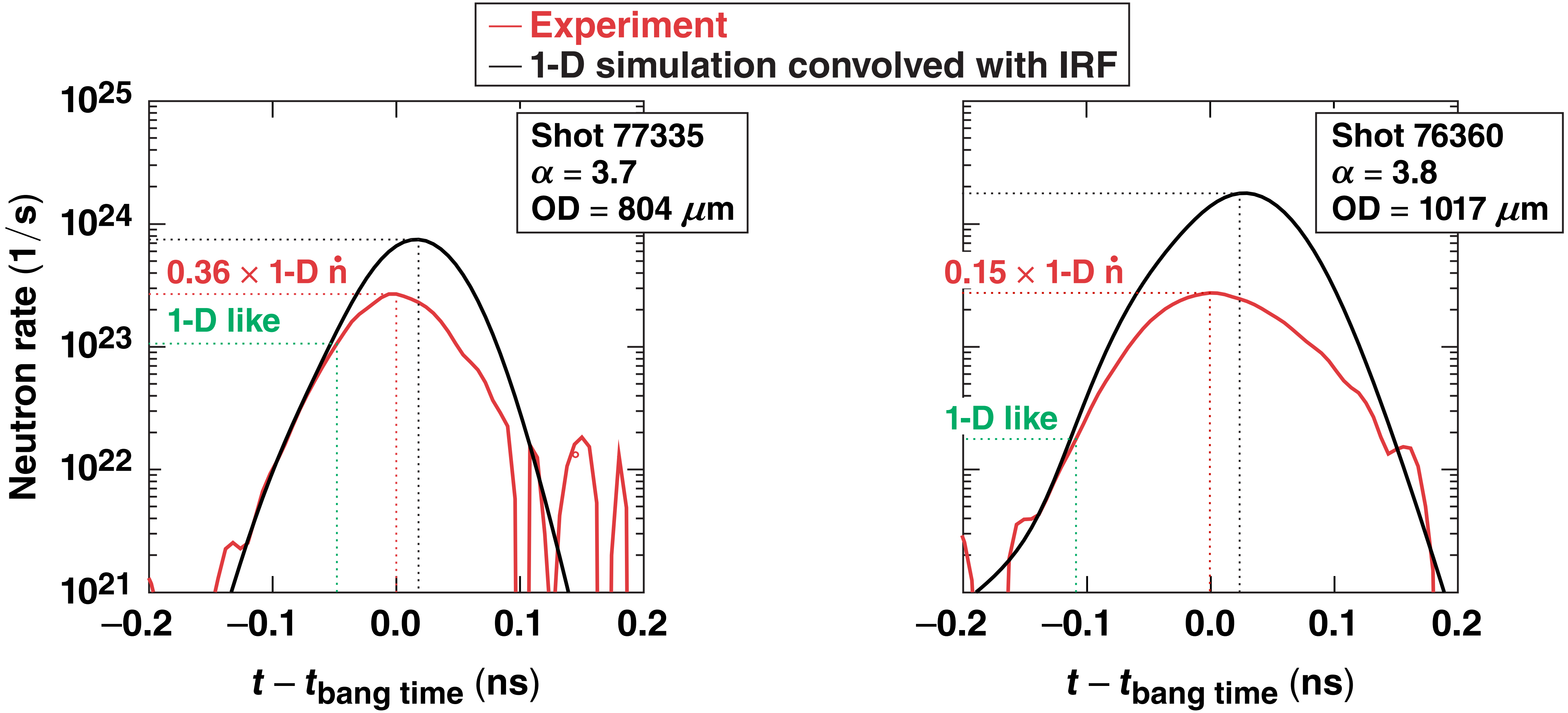


The measured rising slope deviates from the 1-D prediction around 10^{23} s^{-1} and the peak measured neutron rate is 36% of the 1-D value.

ṅ: neutron rate

E24752a

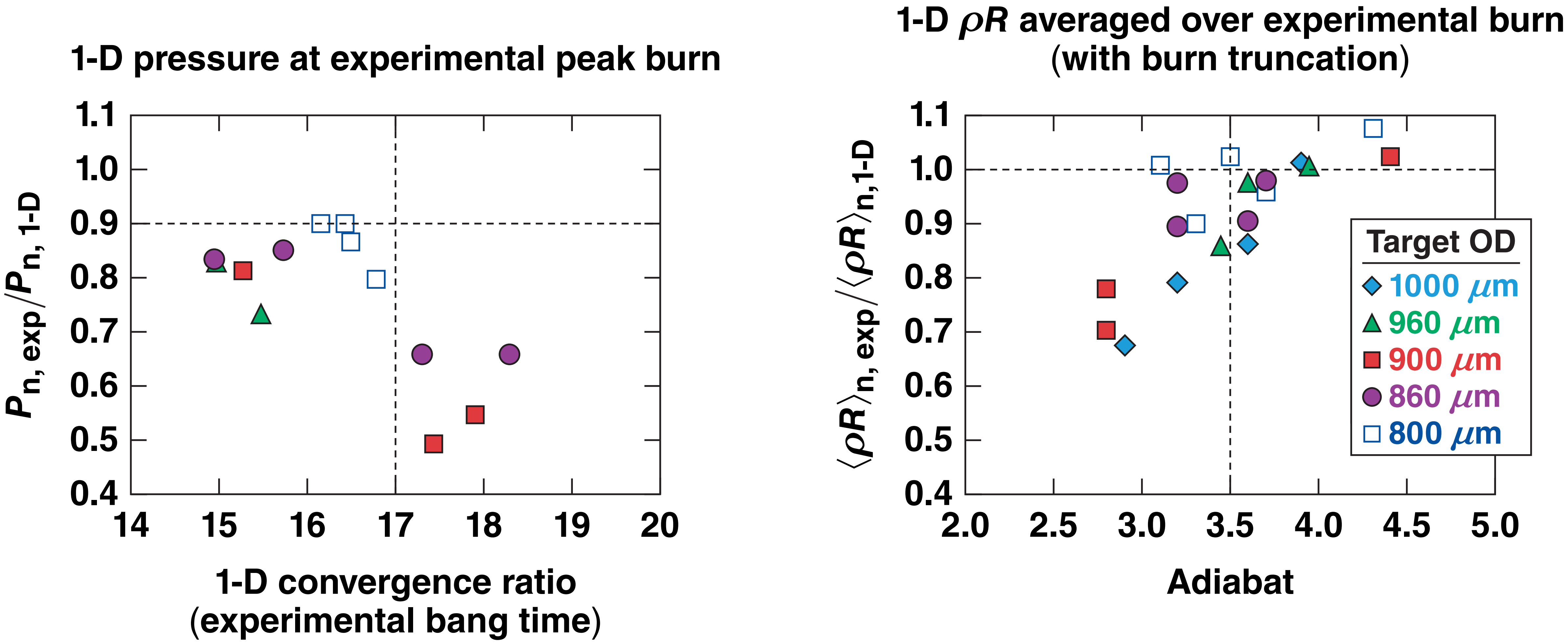
The measured neutron rate shows the onset of burn truncation occurs earlier for the larger targets



The measured rising slope deviates from the 1-D prediction around 10^{22} s^{-1} and the peak measured neutron rate is 15% of the 1-D value.

E24752

The 1-D predictions are closer to the inferred P_{hs} and ρR in implosions with CR < 17 and α > 3.5 when burn truncation is included in the analysis



Low-mode distortion of the hot-spot is the primary factor degrading target performance for the high-adiabat OMEGA DT cryo implosions.

TC12326b

Outline

- 50-Gbar hot-spot pressure
- CBET reduction
- Effect of low-mode distortions on hot-spot pressure
- **Path to 100 Gbar on OMEGA and direct drive on the NIF**

The National Direct-Drive Program has four elements

1. Hydro-equivalent implosions on OMEGA
   - demonstration and physics understanding of ignition-relevant hot-spot pressure (100 Gbar)
   - OMEGA experiments will also demonstrate laser–plasma interaction (LPI) control (CBET mitigation: laser-beam zooming, wavelength detuning, preheat mitigation) strategies

2. LPI, energy coupling, imprint mitigation at MJ-scale plasmas on the NIF
   - will involve both planar and implosion platforms

3. Strategy for conversion of the NIF to SDD
   - cost, schedule, phased approach
   - laser technology development

4. Robust target designs for a range of performances

The National Direct-Drive strategy involves multiple laboratories.

Summary/Conclusions

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- A hot-spot pressure of $P_{\text{hs}} = 56 \pm 7$ Gbar was inferred from x-ray and nuclear diagnostics in direct-drive layered DT implosions on OMEGA
- Cross-beam energy transfer* (CBET) was reduced by increasing the initial target diameter while keeping the laser beam size constant
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D. H. Froula *et al.*, Phys. Rev. Lett. 108, 125003 (2012);
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