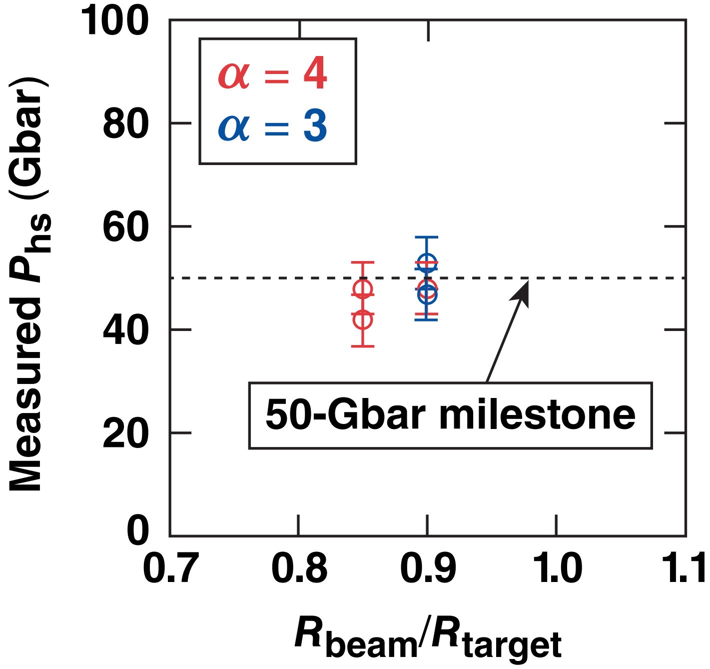
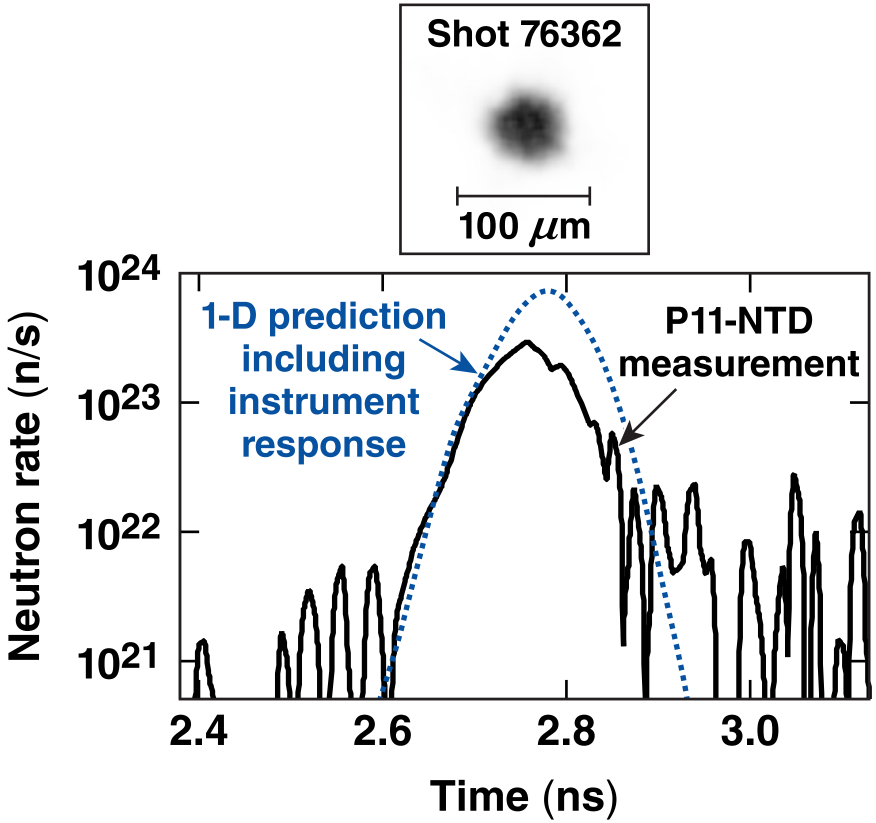
OMEGA Layered DT Cryogenic Implosions





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

Omega Laser Facility
Users Group Workshop
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Summary

Hot-spot pressure is a key performance metric for layered DT cryogenic implosions on OMEGA*

- Cross-beam energy transfer (CBET) reduces the ablation pressure of direct-drive inertial confinement fusion (ICF) targets**
- A CBET mitigation campaign is underway on OMEGA
  - $R_{\text{beam}}/R_{\text{target}}$ scan
  - SG5 phase plates
  - multipulse driver with dynamic bandwidth reduction
- PRELIMINARY: hot-spot pressure of 50 Gbar has been diagnosed
  - hot-spot size: 16-channel Kirkpatrick–Baez gated imager (KBframed)
  - neutron burnwidth: P11 neutron temporal diagnostic (P11-NTD)

An ignition-relevant hot-spot pressure of 100 Gbar will be pursued on OMEGA using beam zooming and multi-ablator targets.

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*V. N. Goncharov *et al*., Phys. Plasmas 21, 056315 (2014);
R. Nora *et al*., Phys. Plasmas 21, 056316 (2014);
C. Cerjan, P. T. Springer, and S. M. Sepke, Phys. Plasmas 20, 056319 (2013).

**I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

Collaborators

V. N. Goncharov, T. C. Sangster, R. Epstein, P. B. Radha, R. Betti, T. R. Boehly, R. Earley, C. J. Forrest, D. H. Froula, V. Yu Glebov, D. R. Harding, E. M. Hill, S. X. Hu, I. V. Igumenshchev, R. T. Janezic, J. H. Kelly, T. J. Kessler, J. P. Knauer, T. Z. Kosc, J. Kwiatkowski, J. A. Marozas, F. J. Marshall, R. L. McCrory, P. W. McKenty, D. D. Meyerhofer, D. T. Michel, J. F. Myatt, J. Puth, N. Redden, J. Reid, W. Seka, W. T. Shmayda, A Shvydky, C. Stoeckl, and M. D. Wittman

University of Rochester
Laboratory for Laser Energetics

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

Massachusetts Institute of Technology

Outline

OMEGA layered DT cryogenic implosions

- Theory
  - CBET
  - hot-spot pressure
- Experiment
  - layered DT cryogenic targets
  - laser
  - diagnostics
- CBET mitigation campaign
  - $R_{\text{beam}}/R_{\text{target}}$ scan
- Path to 100 Gbar

Theory

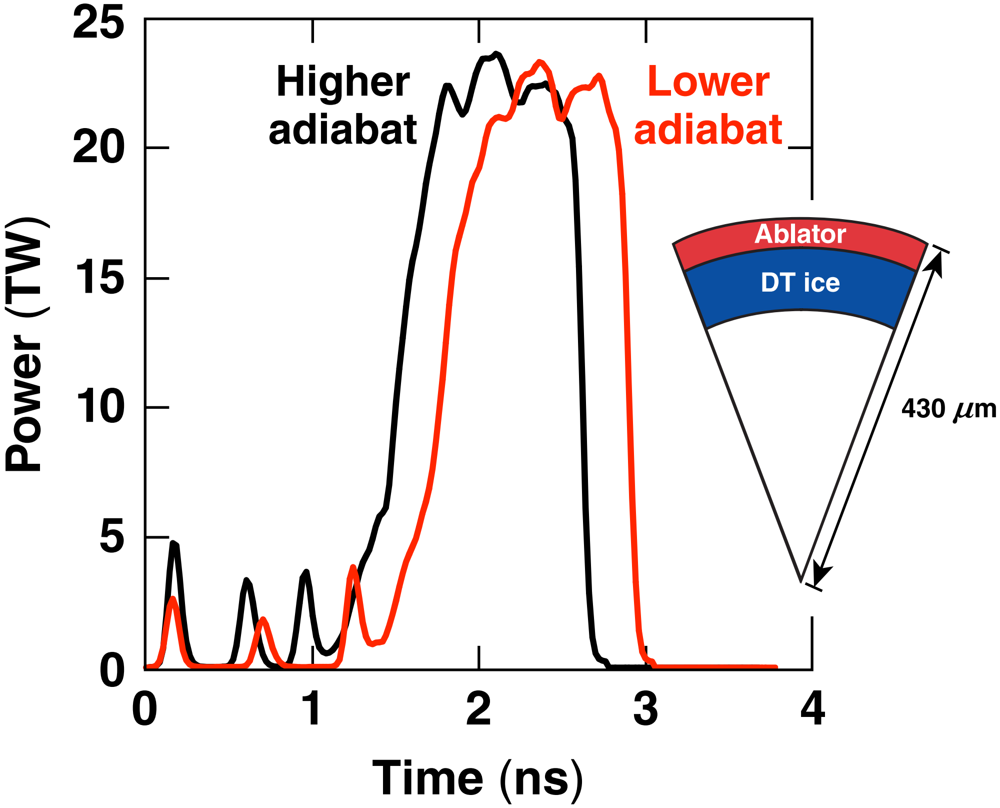
Direct-drive target performance is optimized by varying implosion velocity, in-flight aspect ratio (IFAR), fuel adiabat, and ablator material

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

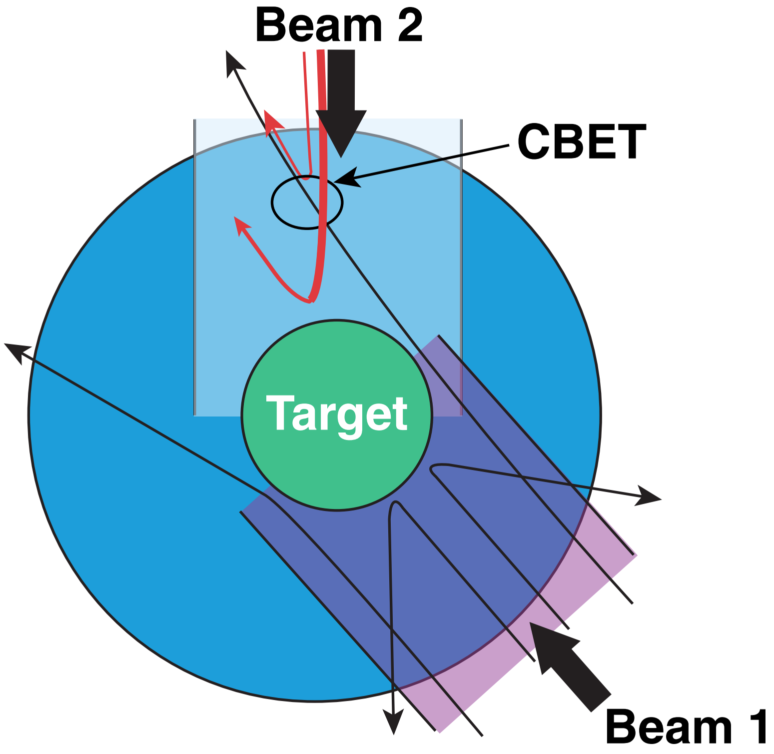
Adiabat
$\alpha = P/P_{\text{Fermi}}$

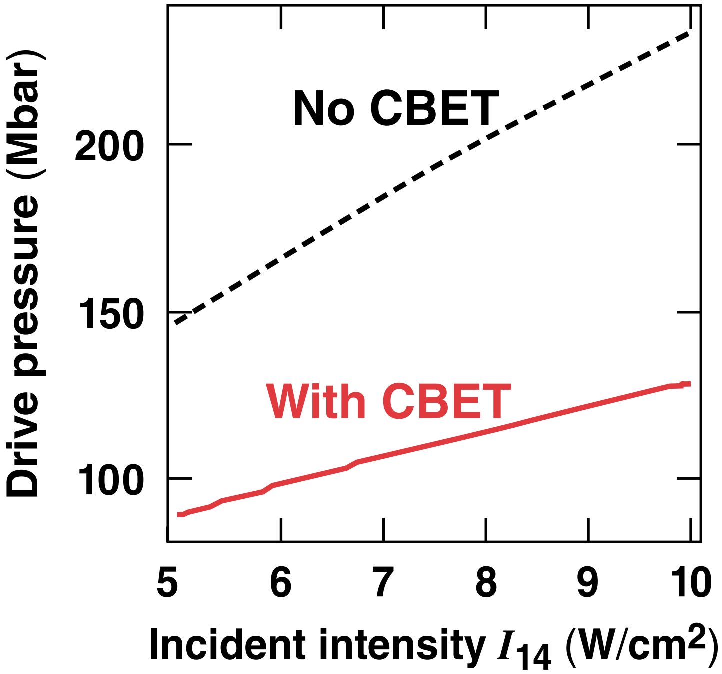
IFAR = shell radius/ shell thickness

Adiabat and IFAR are controlled by pulse shaping



CBET* reduces the laser drive and ablation pressure





CBET occurs during the main laser drive.

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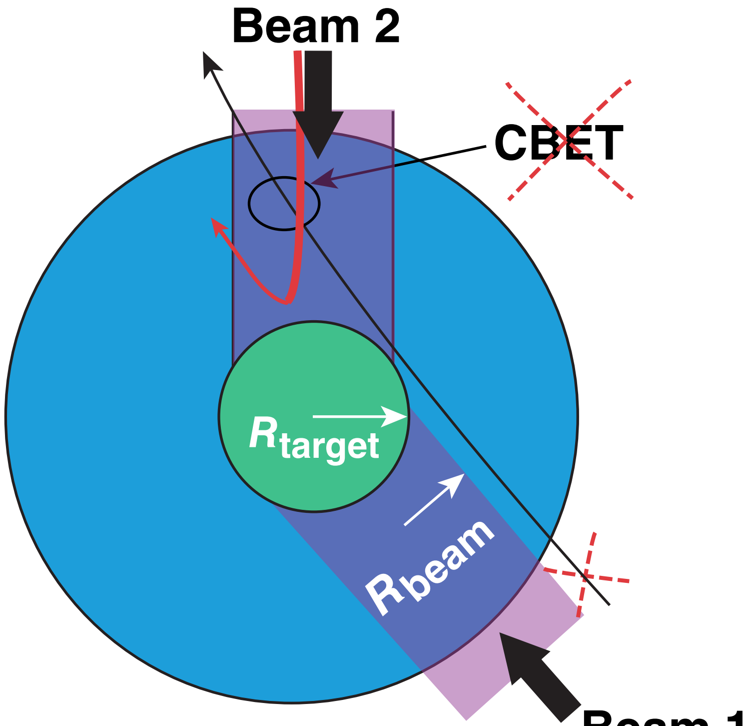
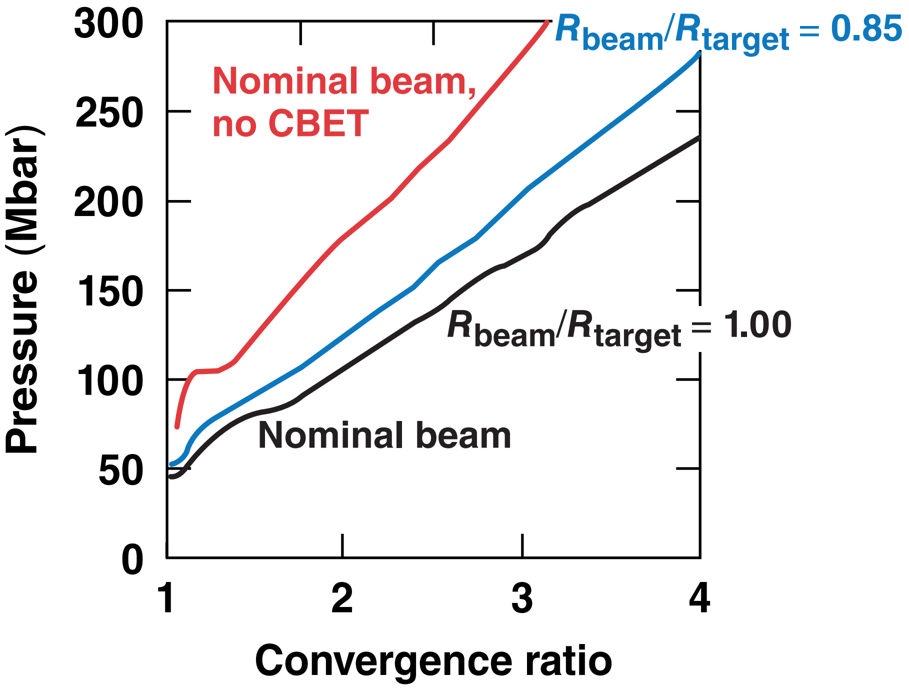
*I. V. Igumenshchev *et al.*, Phys. Plasmas 17, 122708 (2010).

Theory

Reducing the ratio of $R_{\text{beam}}/R_{\text{target}}$ is a proposed CBET mitigation technique

Using smaller beams at the main drive reduces CBET





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*I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

Theory

Hot-spot pressure is the key ignition parameter*

Hot-spot ignition condition

$$(\rho R)_{\mathrm{hs}} \times T_{\mathrm{i}} > 0.35\ \mathrm{g/cm^2} \times 5\ \mathrm{keV}$$

$$\boxed{P_{\mathrm{DT}} = 2\rho T / 2.5\, m_p}$$

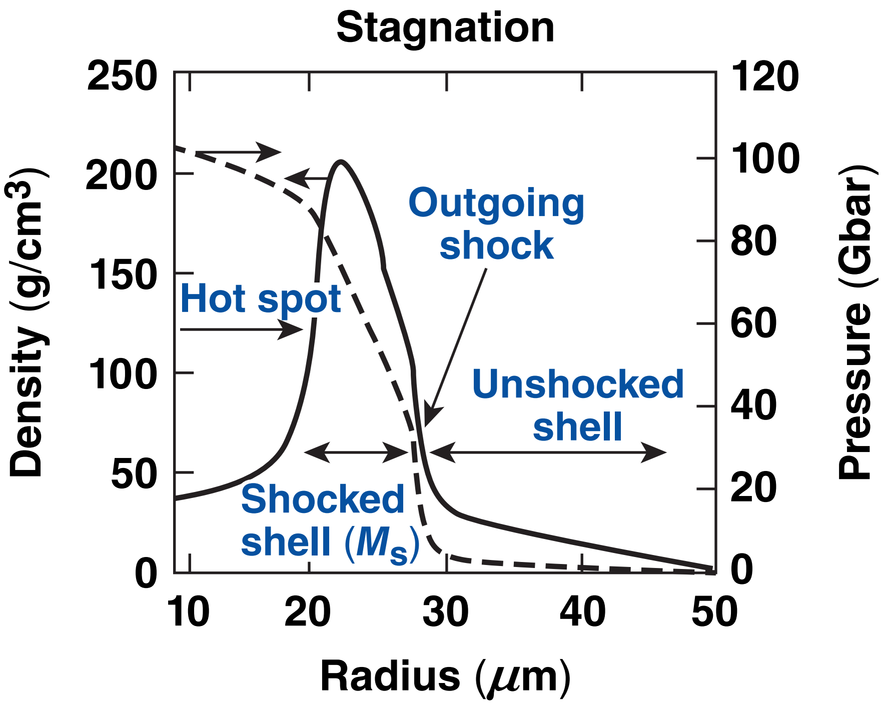
$$P_{\mathrm{hs}} > 100\ \mathrm{Gbar}\left(\frac{100\ \mu\mathrm{m}}{R_{\mathrm{hs}}}\right)$$

Shocked shell fraction

$$\boxed{f_{\mathrm{k}} E_{\mathrm{k}} = 2\pi p_{\mathrm{hs}} R_{\mathrm{hs}}^3,\ f_{\mathrm{k}} \sim M_{\mathrm{s}} / M}$$

Hot-spot energy

$$\boxed{P_{\mathrm{hs}} > 250\ \mathrm{Gbar}\left(\frac{\overbrace{f_{\mathrm{k}} E_{\mathrm{k}}}}{10\ \mathrm{kJ}}\right)^{-1/2}}$$



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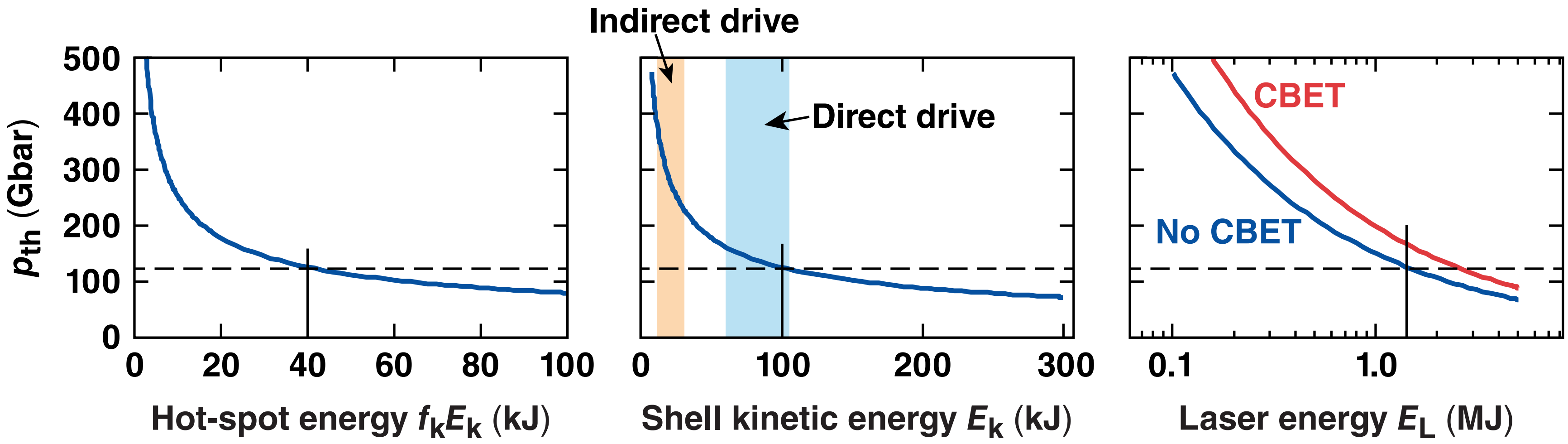
*V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

Theory

Less hot-spot pressure is required to ignite a design with larger shell kinetic energy

$$P_{hs} > P_{th} = 250\ \text{Gbar}\left(\frac{f_k E_k}{10\ \text{kJ}}\right)^{-1/2}$$

$f_k \sim 40\%$ to 50%, $E_k = f_{hydro}\, E_L$, $f_{hydro} \sim 6\%$ to 7% (3.5% to 4.0% with CBET)



The required stagnation pressure is 120 Gbar without CBET and 150 Gbar with CBET.

Theory

Hot-spot pressure is inferred from the measured hot-spot size, burnwidth, $\langle T_i \rangle$, and neutron yield

Shot 76603

$R_{hs} = R_{17\%} = 21.8\ \mu m$

$\Delta t_{x\ ray} = 82 \pm 5\ ps \rightarrow \Delta t_{burn}(\text{inferred}) = 88 \pm 5\ ps$

$Y = 4.1 \times 10^{13}$

$\langle T_i \rangle = 2.9\ keV$

$$\dot{N}_{mx} = \frac{Y}{\Delta t_{burn}} 2 \sqrt{\frac{\ln 2}{\pi}} = 6.3 \times 10^{23}\ 1/s$$

Betti's hot-spot profile $T = T_c \dfrac{\left[1 - \left(r/R_{hs}\right)^2\right]^{2/5}}{1 - 0.15\left(r/R_{hs}\right)^2}$

$$\langle T \rangle = \frac{\int_{V_{hs}} T n_D n_T \langle \sigma v \rangle dV}{\dot{N}_{mx}} \rightarrow T_c = 4\ keV \simeq 1.23 \langle T \rangle$$

$$\dot{N}_{mx} \sim p_{bang}^2 \int_{V_{hs}} \frac{\langle \sigma v \rangle}{T^2} dV \rightarrow p_{bang} \sim \sqrt{\frac{\dot{N}_{mx}}{\int \langle \sigma v \rangle \frac{dV}{T^2}}} = 53 \pm 5\ \text{Gbar}$$

Current OMEGA cryogenic implosions reach ~0.44 of the hot-spot pressure required for ignition (without CBET) and ~0.35 with CBET.

Outline

OMEGA layered DT cryogenic implosions

- Theory
  - CBET
  - hot-spot pressure
- **Experiment**
  - **layered DT cryogenic targets**
  - **laser**
  - **diagnostics**
- CBET mitigation campaign
  - $R_{\mathrm{beam}}/R_{\mathrm{target}}$ scan
- Path to 100 Gbar

Tritium Fuel Supply

The new Isotope Separator System (ISS)* provides high-purity (99.7%) T_2 fuel

- 12 mCi released out of 8500 Ci processed in September 2014
- Before: T:D:H was 34%:60%: 5% (estimated)
- After: T:D:H is 60:40: <0.1% (estimated)

The 60:40 T:D ratio was chosen to provide a 50:50 mixture in the gas phase (fractionation) of a layered capsule.

E23693b

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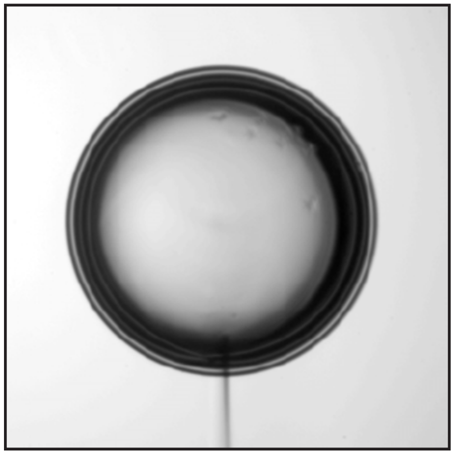
*Developed jointly with Savannah River National Laboratory.

Layered DT cryogenic targets are produced routinely with 1-μm rms layer smoothness

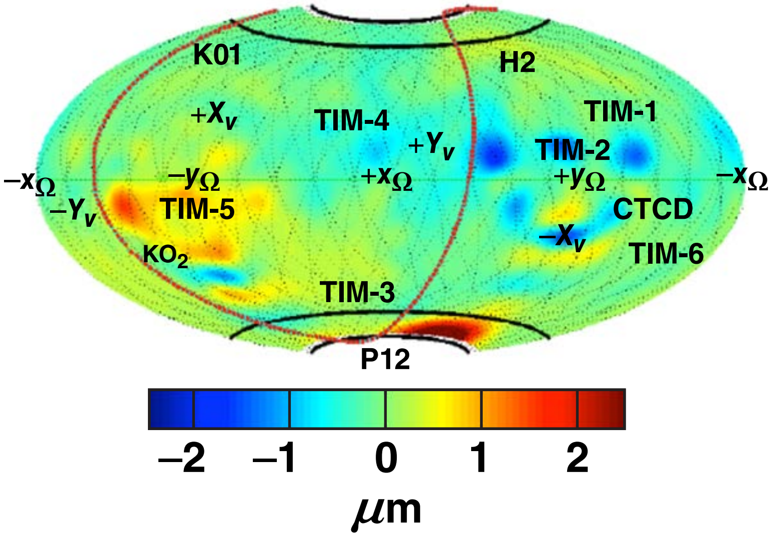
<u>3-D target metrology analysis</u>
Thickness: 53.5 μm
rms: 0.92 μm
Measured diameter: 910.2 μm

Shadowgraph
x view



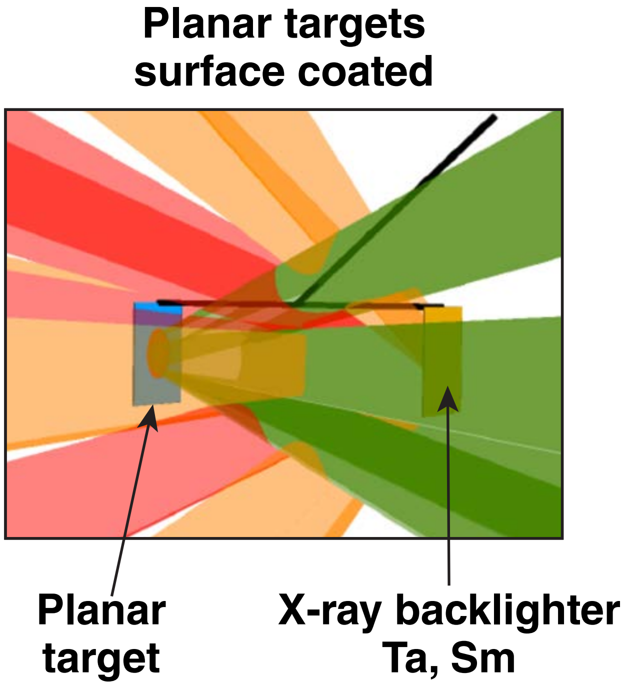
Shadowgraph
y view

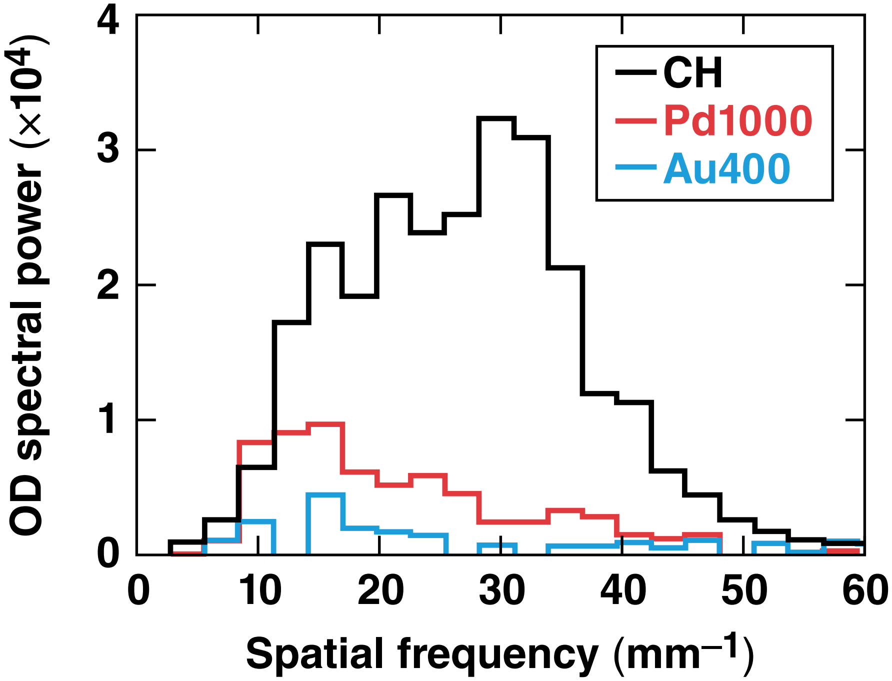
3-D reconstruction
of deviations from
average DT thickness



Thin Au overcoat layers have been shown to reduce laser imprint*

OMEGA planar CH Rayleigh–Taylor experiment**





Thin Au overcoat layers are being studied with layered DT cryogenic targets to mitigate laser imprint and the effects of target surface debris.

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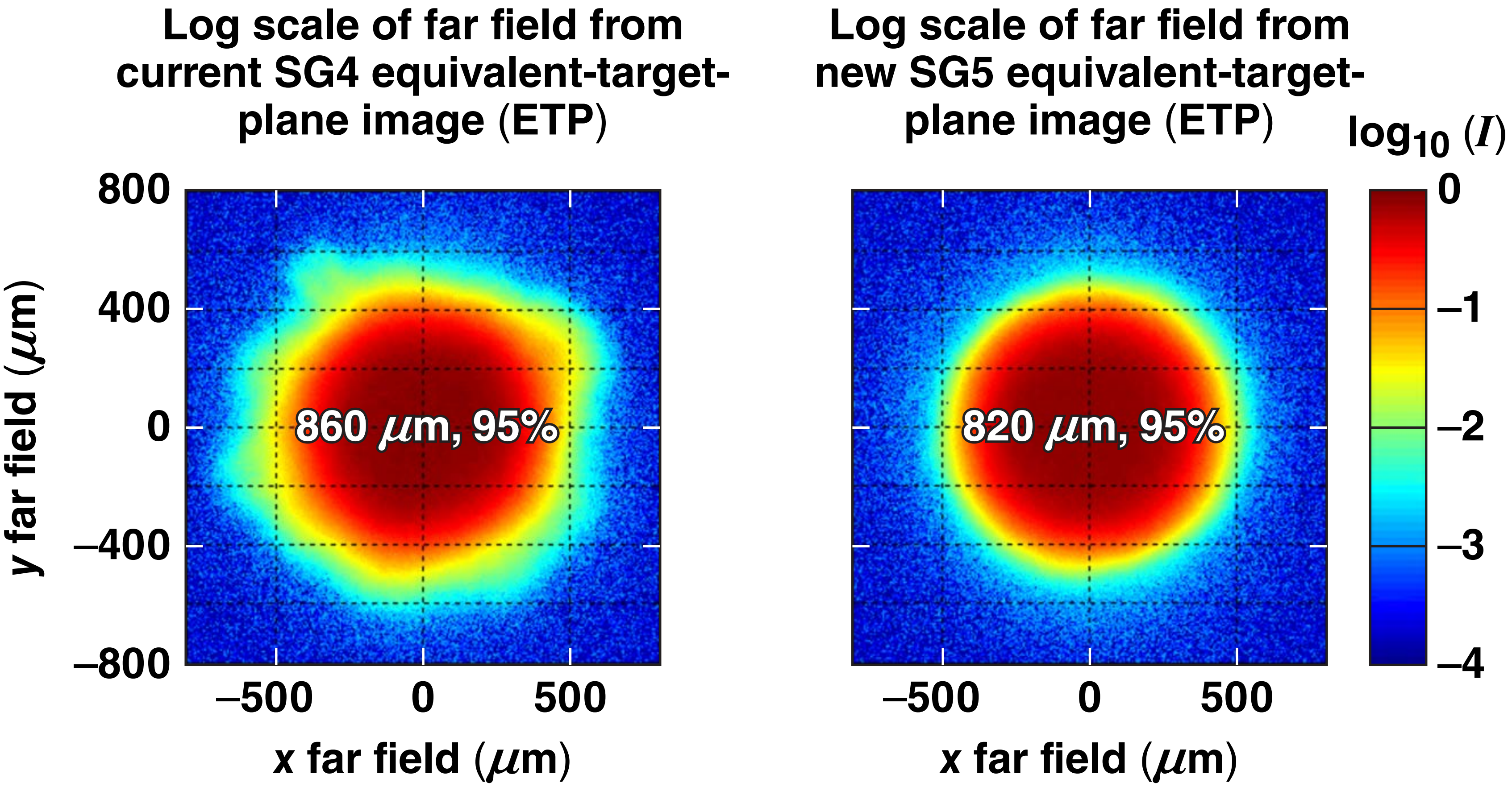
*S. P. Obenschain *et al*., Phys. Plasmas 9, 2234 (2002).

**G. Fiksel, Laboratory for Laser Energetics, private communication (2015).

OMEGA Phase Plates

A new set of phase plates designed to improve on-target drive uniformity and reduce CBET is used

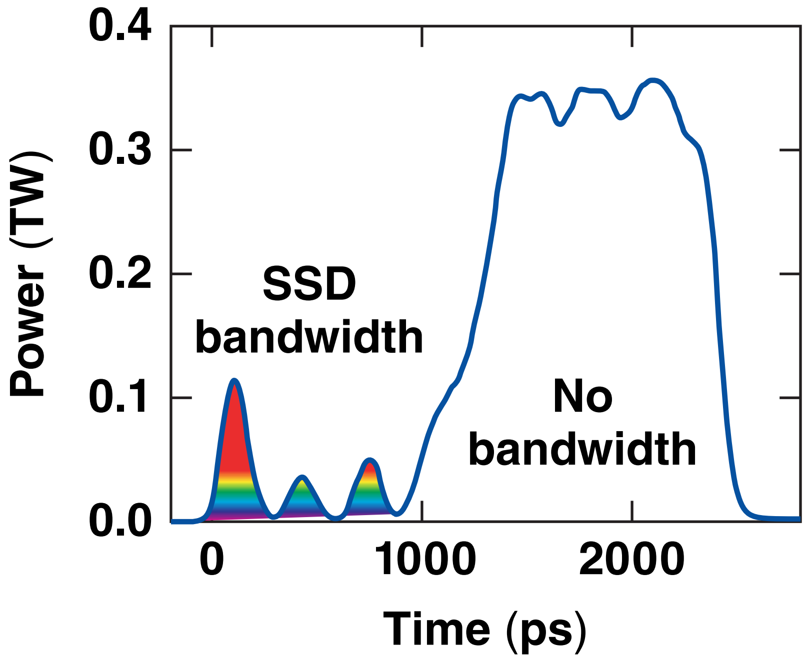


Less light blows by the target with SG5 compared to SG4 phase plates.

OMEGA Laser Driver

The multipulse driver (MPD) with dynamic bandwidth reduction (DBR) provides more laser energy on target

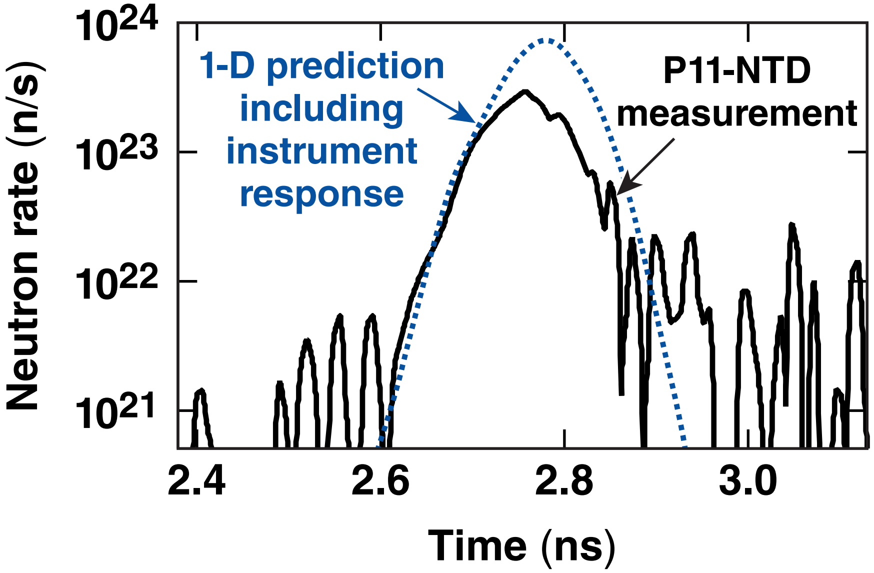
- **Front-end modifications have been made to co-propagate two separate pulse shapes in all 60 OMEGA beams**
- **2-D smoothing by spectral dispersion (SSD) can be applied to either one of the two pulse shapes**
- **DBR applies SSD to only the pickets and provides increased drive energy**



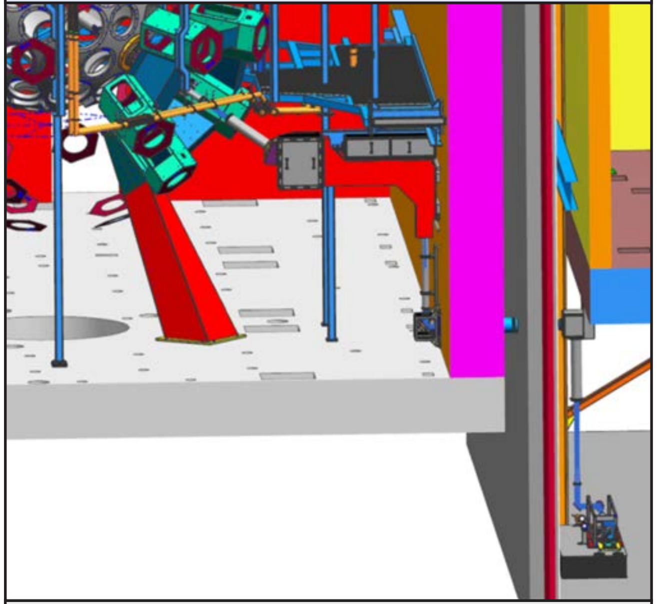
The arbitrary waveform generator (AWG) improved laser pulse shaping, pulse contrast, and pulse stability.

E23690a

A new neutron temporal diagnostic (P11-NTD) provides an accurate measurement of the neutron burnwidth



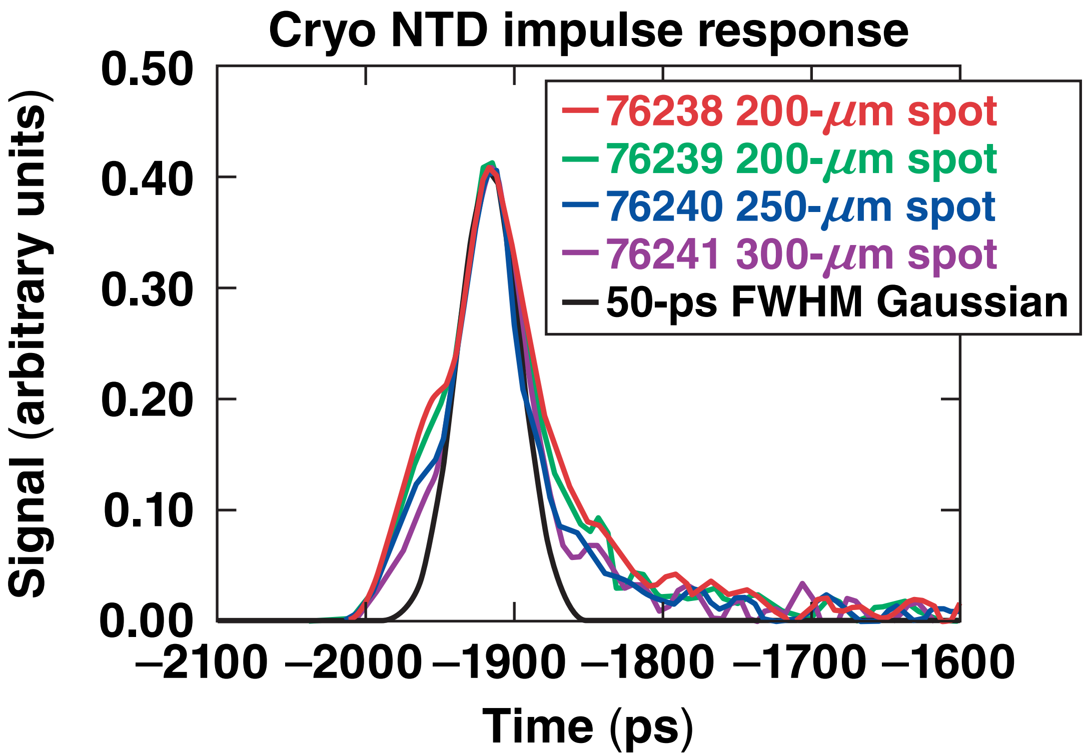
The CryoNTD is located in P11 with optical transport to a streak camera in the OMEGA EP plenum (Signal to background ~ 200)



The estimated impulse response is ~50 ps, adequate for 50- to 60-Gbar pressures and widths of 70 to 90 ps

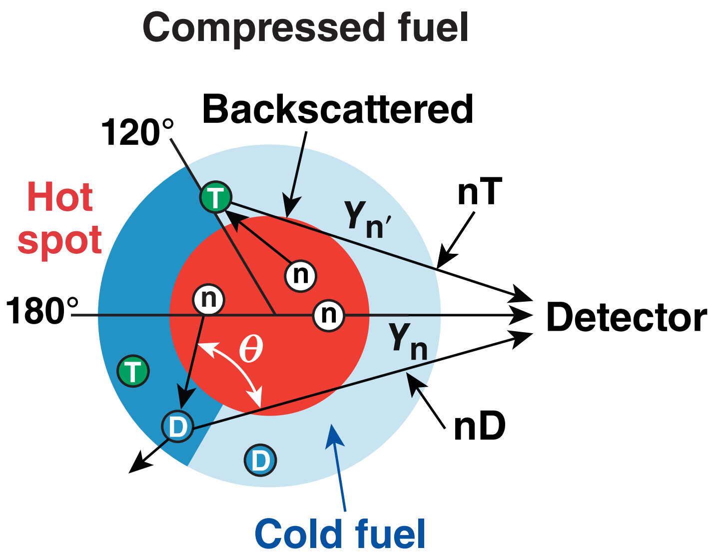
OMEGA Diagnostics

P11-NTD has an impulse response of ~40±10 ps and an absolute timing calibration of 50 ps



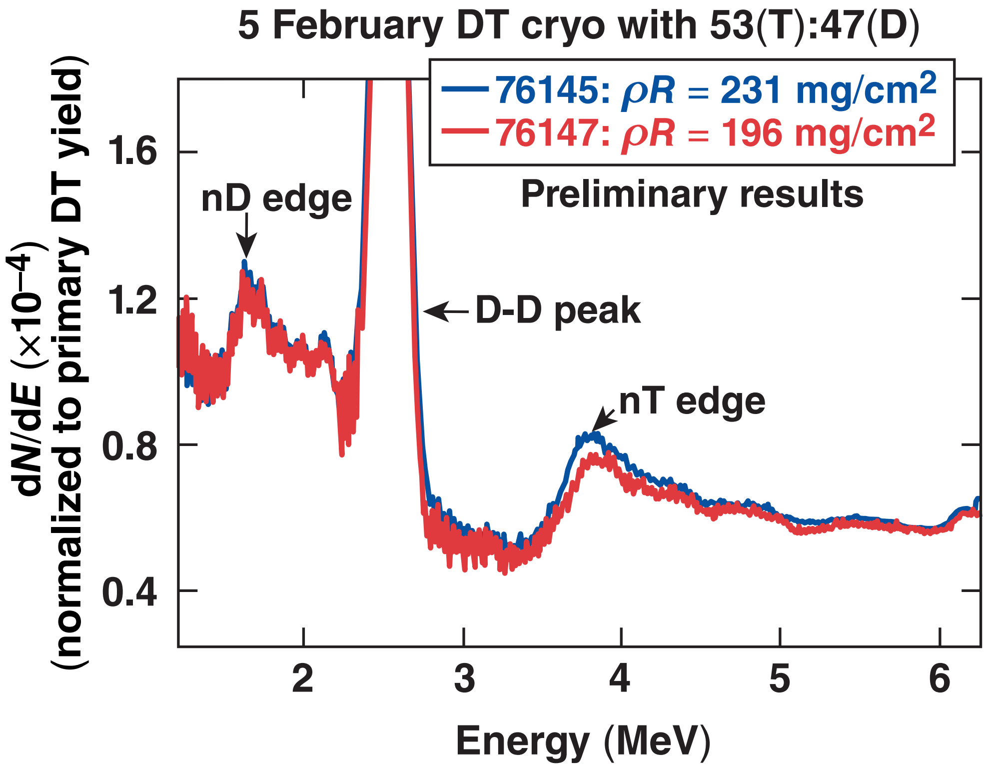
- The impulse response was measured using 10-ps OMEGA EP pulses
- Assuming a width of the x-ray signal of ~30±10 ps, the impulse response of P11-NTD deconvolves to ~40±10 ps
- P11-NTD is calibrated against NTD and has the same absolute timing accuracy of 50 ps

The *ρR* is diagnosed using the downscattered neutrons in the 3.5- to 6-MeV range recorded with a neutron time-of-flight detector (nTOF)*



$$E_R = E_n - \frac{4A}{(1+A)^2}(\cos\theta^2)E_n$$

$$\rho R \propto \frac{Y_{DS}\,(3.5 \text{ to } 6\,\text{MeV})}{Y_{DT}}$$



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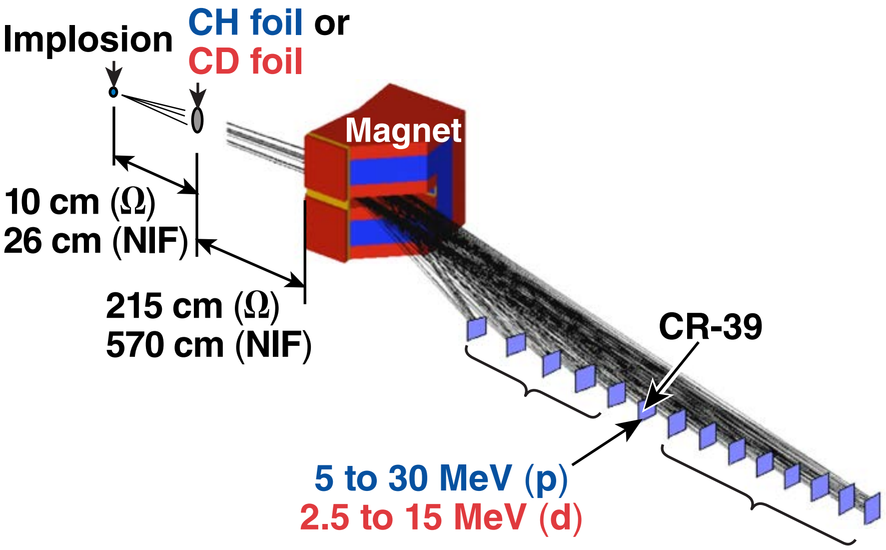
*C. J. Forrest *et al.*, Rev. Sci. Instrum. 83, 10D919 (2012).

The ρR is diagnosed using the downscattered neutrons in the 10- to 12-MeV range with the magnetic recoil spectrometer (MRS)*



Implosion

CH foil or **CD foil**

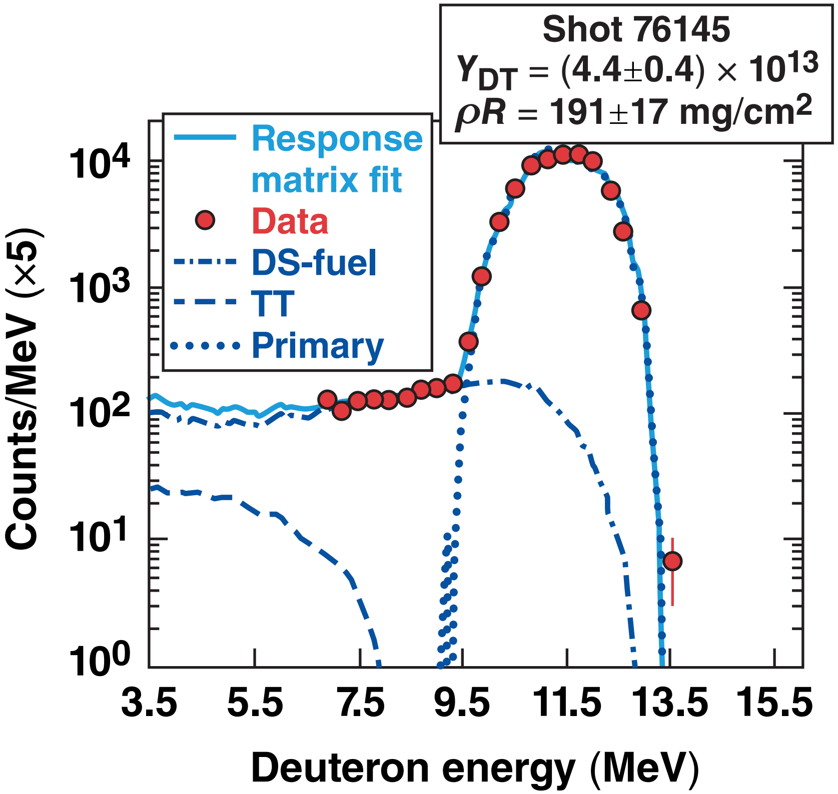
Magnet

10 cm (Ω)
26 cm (NIF)

215 cm (Ω)
570 cm (NIF)

CR-39

5 to 30 MeV (p)
2.5 to 15 MeV (d)



Shot 76145
$Y_{DT} = (4.4 \pm 0.4) \times 10^{13}$
$\rho R = 191 \pm 17\ \text{mg/cm}^2$

Analysis assumes 48% D, 51% T, 1% H

$$\rho R \propto \frac{Y_{DS}\left(10 \text{ to } 12 \text{ MeV}\right)}{Y_{DT}}$$

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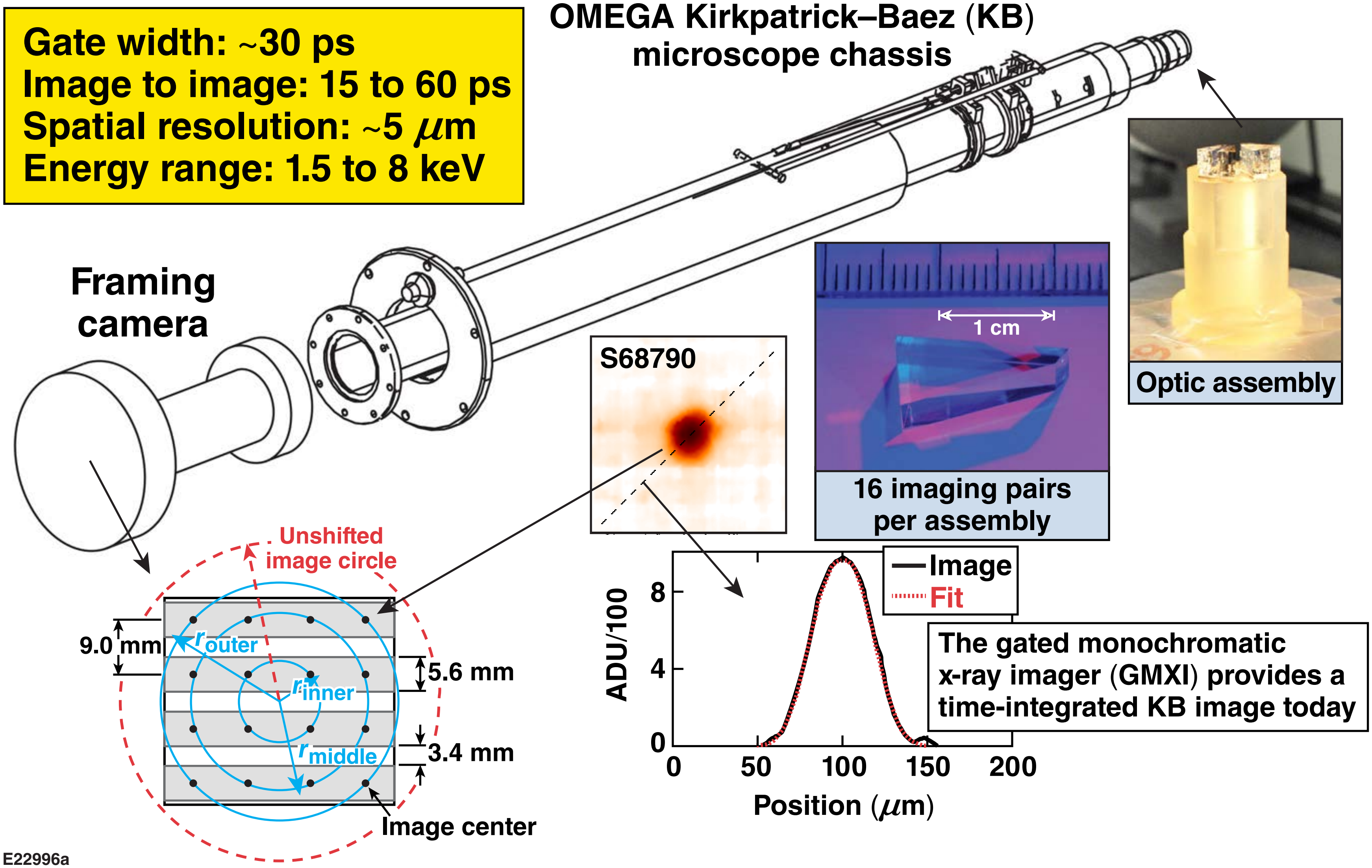
*J. Frenje *et al.*, Phys. Plasmas 17, 056311 (2010).

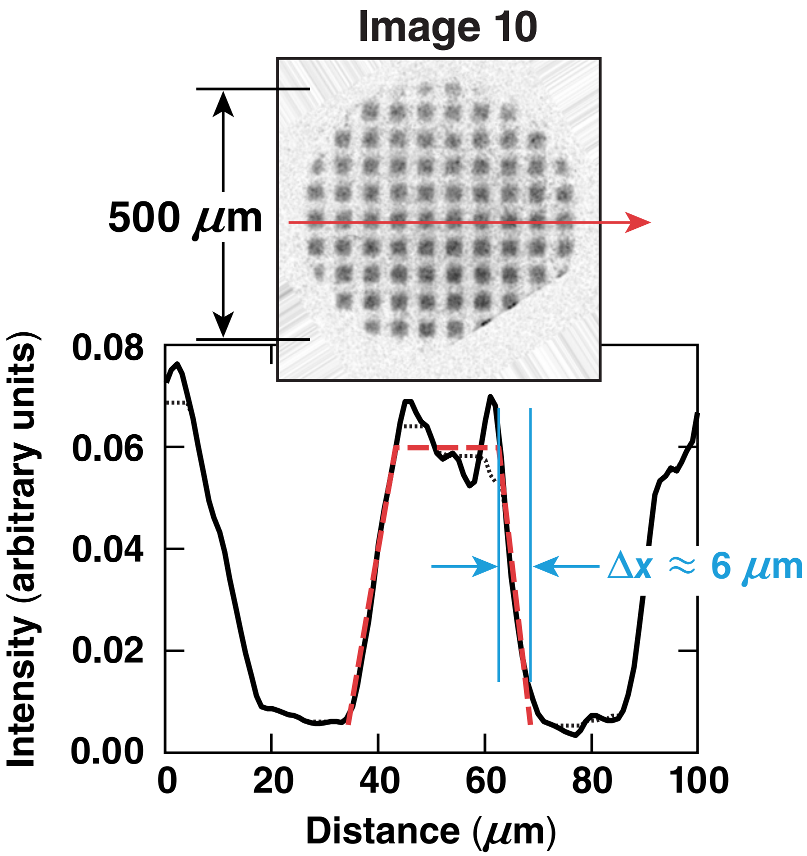
A framed, 16-channel Kirkpatrick–Baez imager provides time-resolved images of the core around stagnation

Gate width: ~30 ps
Image to image: 15 to 60 ps
Spatial resolution: ~5 μm
Energy range: 1.5 to 8 keV



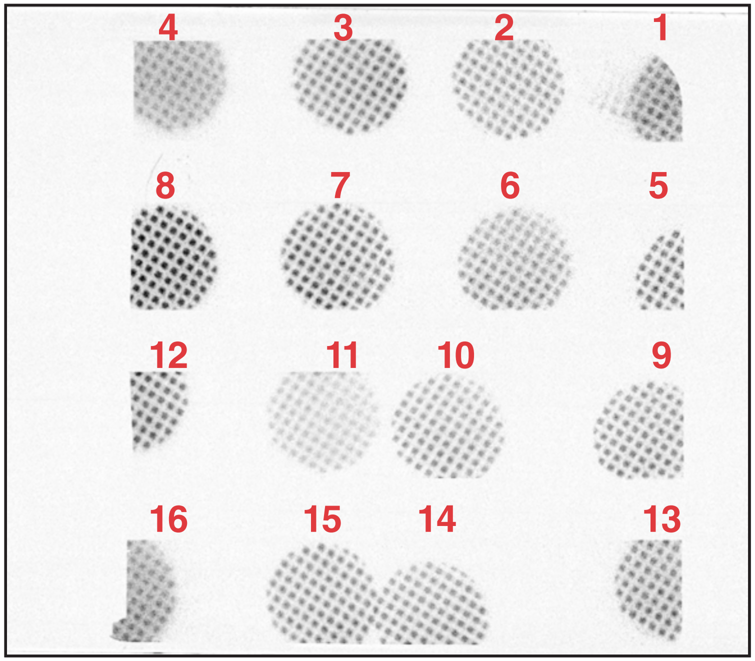
The gated monochromatic x-ray imager (GMXI) provides a time-integrated KB image today

KBframed optic magnification and framed resolution have been measured using an x-ray backlit grid on OMEGA



Preliminary analysis → M = 12 with 6-μm resolution

KBframed OMEGA shot 76806



M = 12.0 within 1%
Resolution (FWHM* of the PSF) ≈ 6 μ**
varies from image to image

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*Full width at half maximum
**Point spread function

Outline

OMEGA layered DT cryogenic implosions

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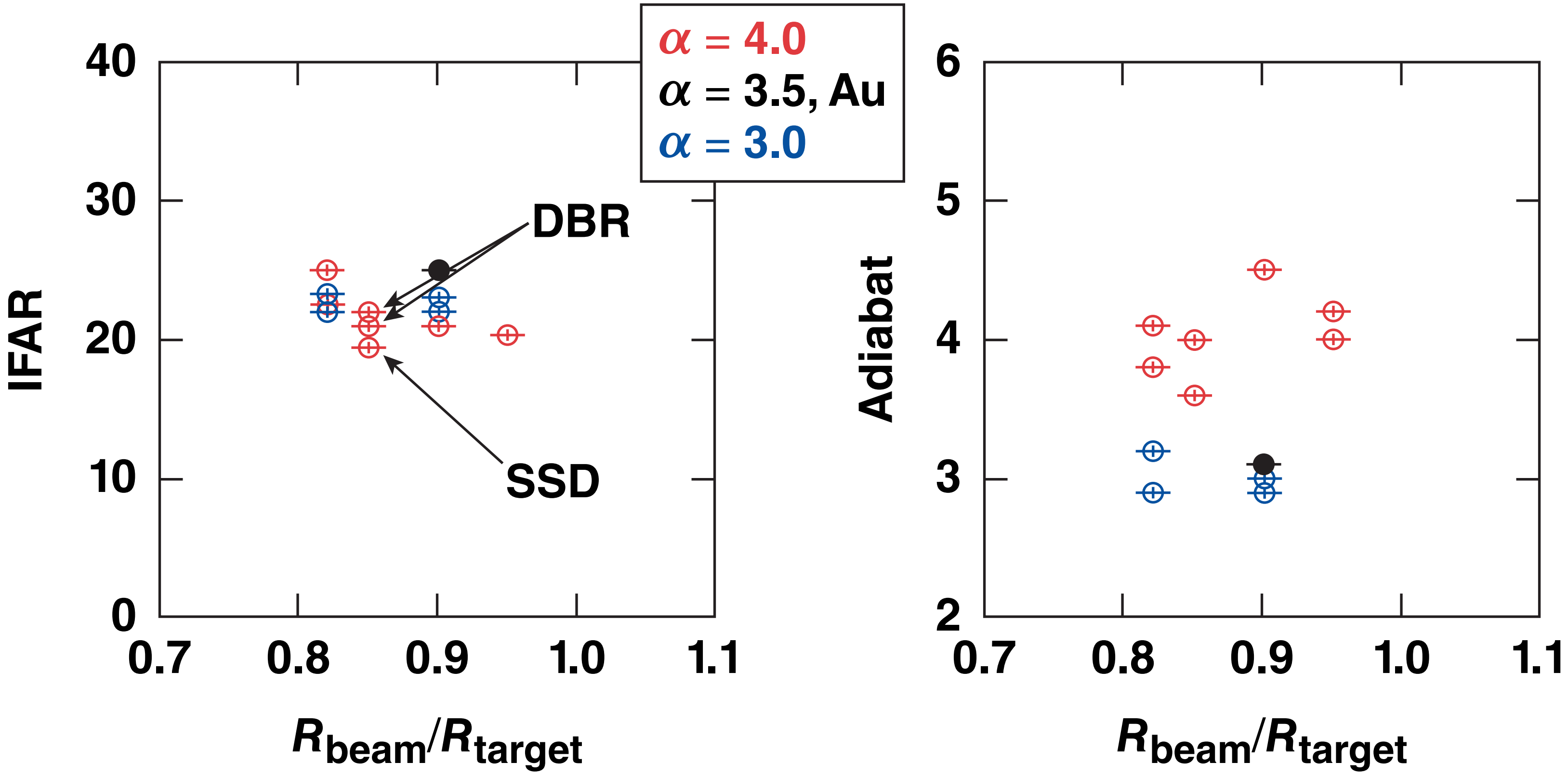
  - CBET
  - hot-spot pressure
- Experiment
  - layered DT cryogenic targets
  - laser
  - diagnostics
- **CBET mitigation campaign**
  - **$R_{\mathrm{beam}}/R_{\mathrm{target}}$ scan**
- Path to 100 Gbar

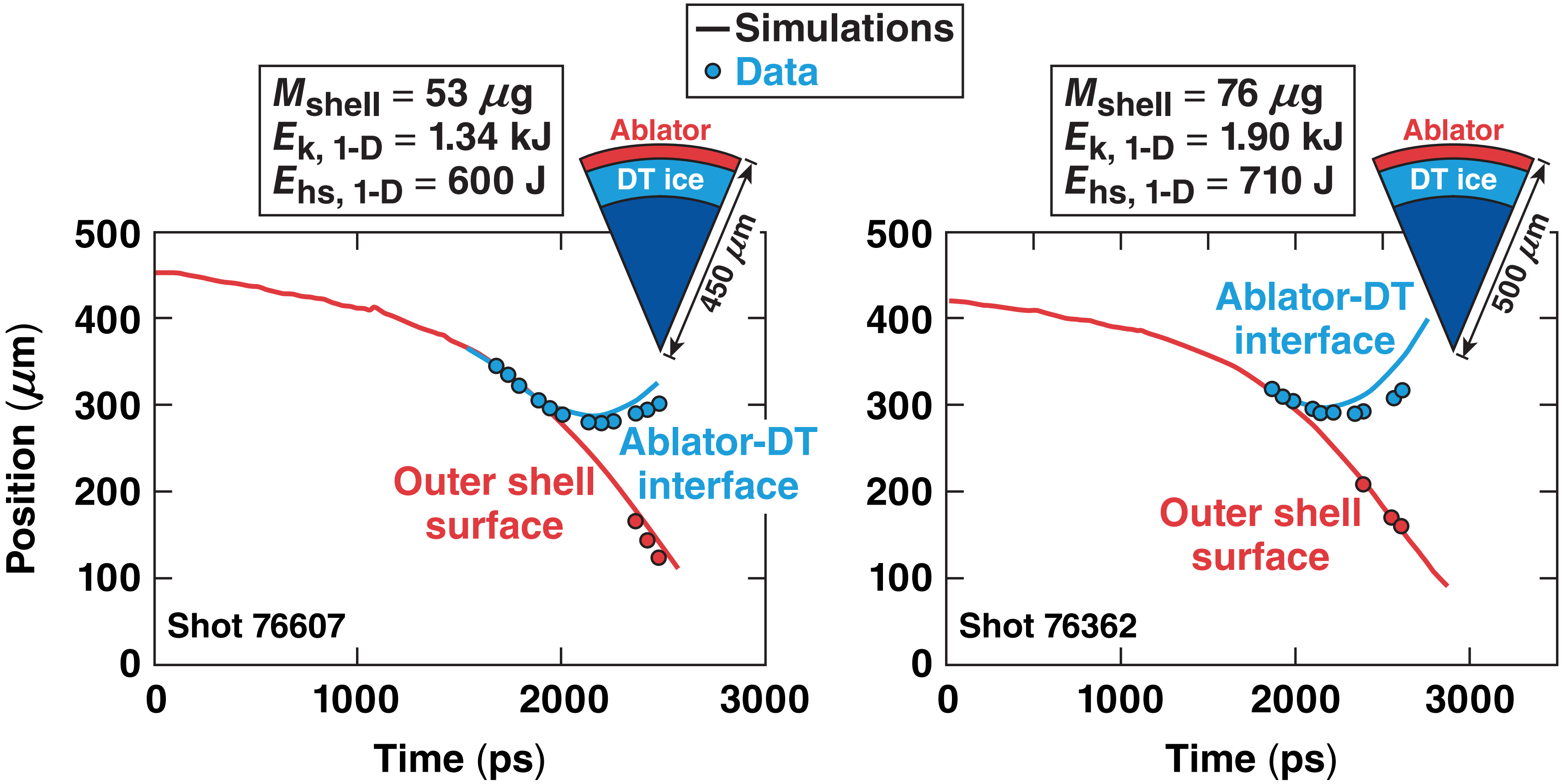
The effects of CBET and two-plasmon decay (TPD) on target performance were studied by varying $R_{\text{beam}}/R_{\text{target}}$ and keeping IFAR and adiabat constant



The calculated implosion velocity was 3.6 × 10^7 cm/s for all shots except the one with $R_{\text{beam}}/R_{\text{target}}$ = 0.85 and SSD (3.3 × 10^7 cm/s).

Energy coupling to the shell is diagnosed using gated x-ray imaging of coronal plasma

V_{imp}, theory = 3.5×10^7 cm/s for both designs



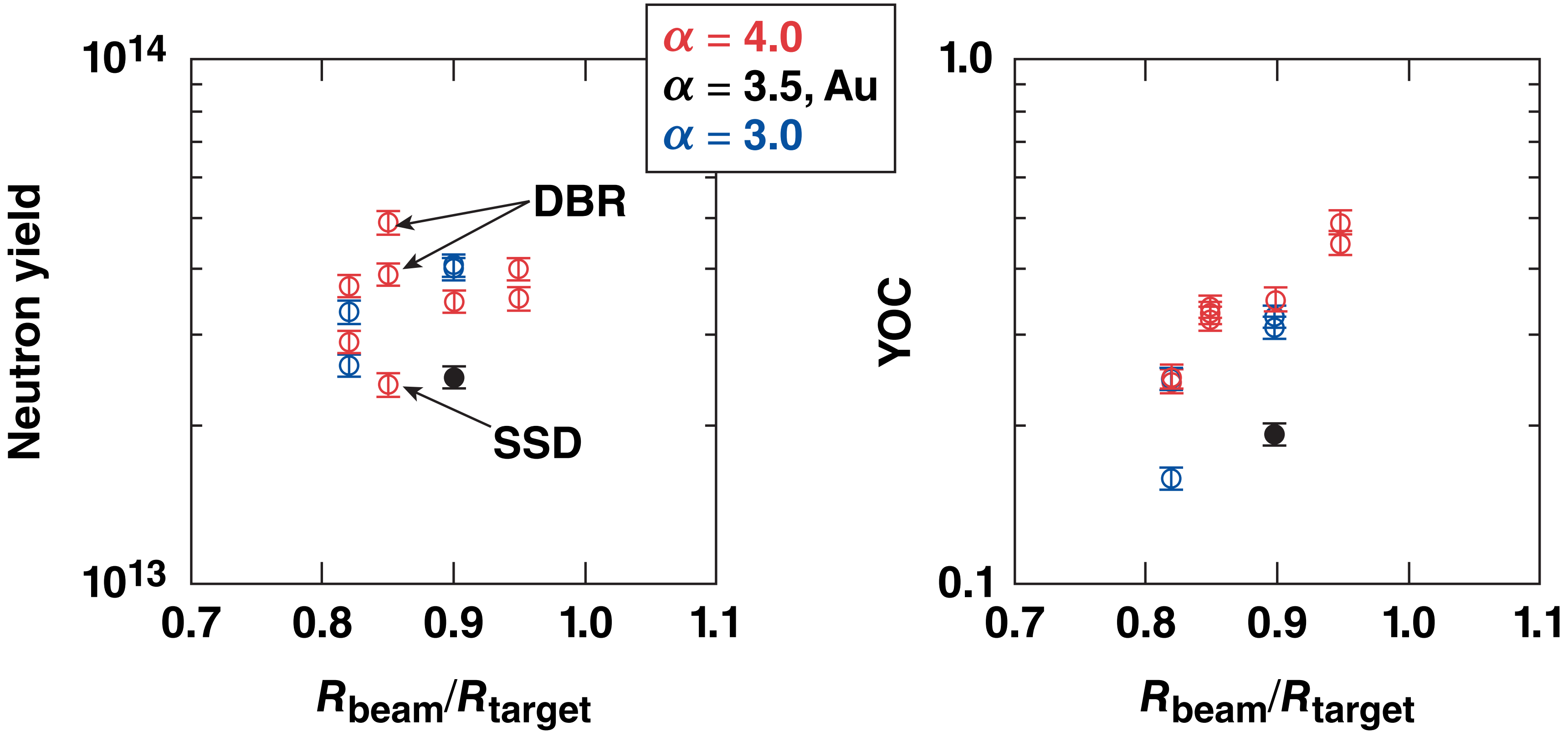
$M_{\text{shell}} = 53\ \mu g$
$E_{\text{k, 1-D}} = 1.34$ kJ
$E_{\text{hs, 1-D}} = 600$ J

$M_{\text{shell}} = 76\ \mu g$
$E_{\text{k, 1-D}} = 1.90$ kJ
$E_{\text{hs, 1-D}} = 710$ J

The CBET model is in reasonable agreement with measurements.

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

The neutron yield over clean (YOC) increases as $R_{\text{beam}}/R_{\text{target}}$ increases



Similar YOC was observed for implosions having either DBR or 2-D SSD ⟶ more UVOT* with DBR (29 kJ versus 26 kJ).

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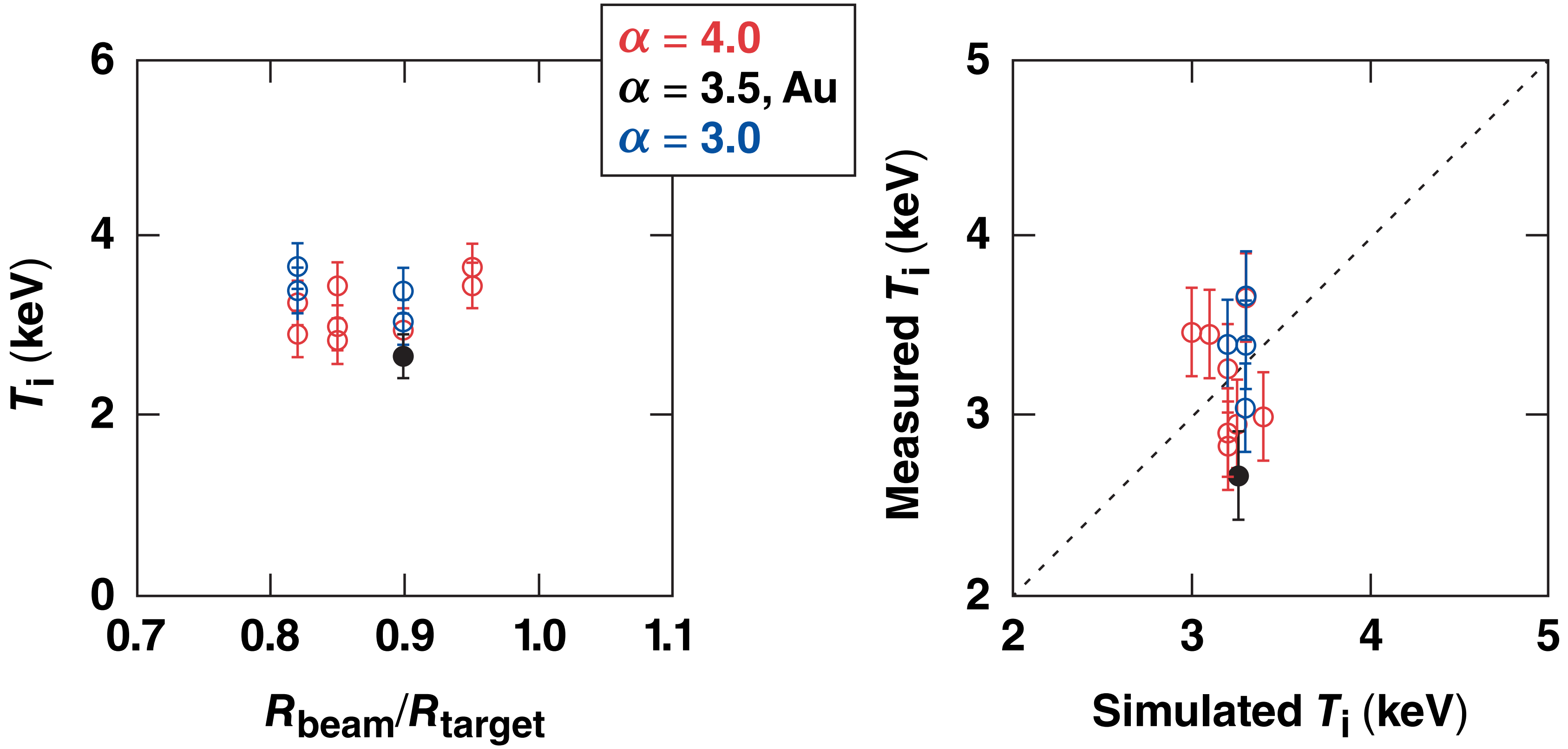
*Unsheared ultraviolet laser energy on target

The ion temperature is inferred from the nTOF diagnostic



The lowest T_i is used to infer the hot-spot pressure for each implosion.

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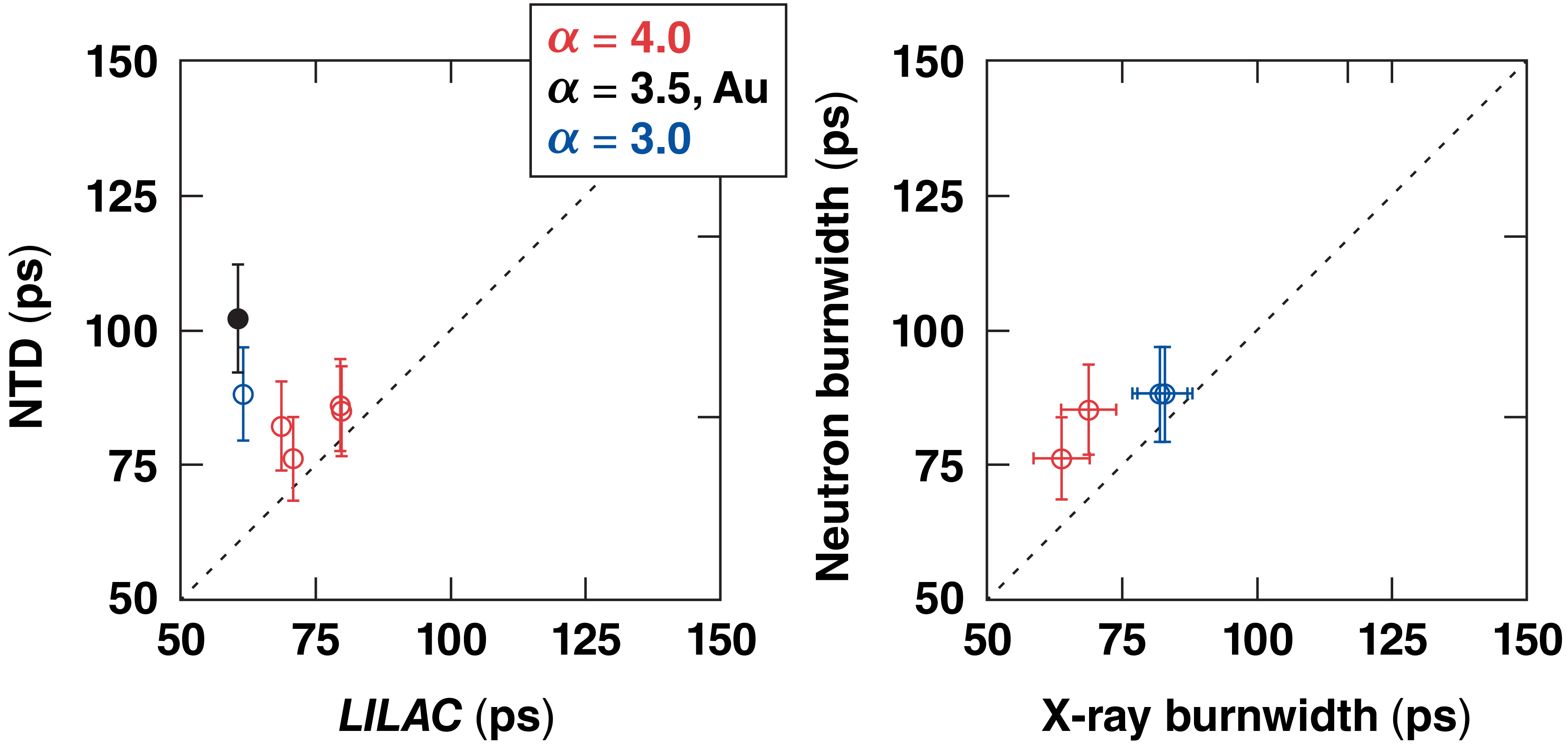
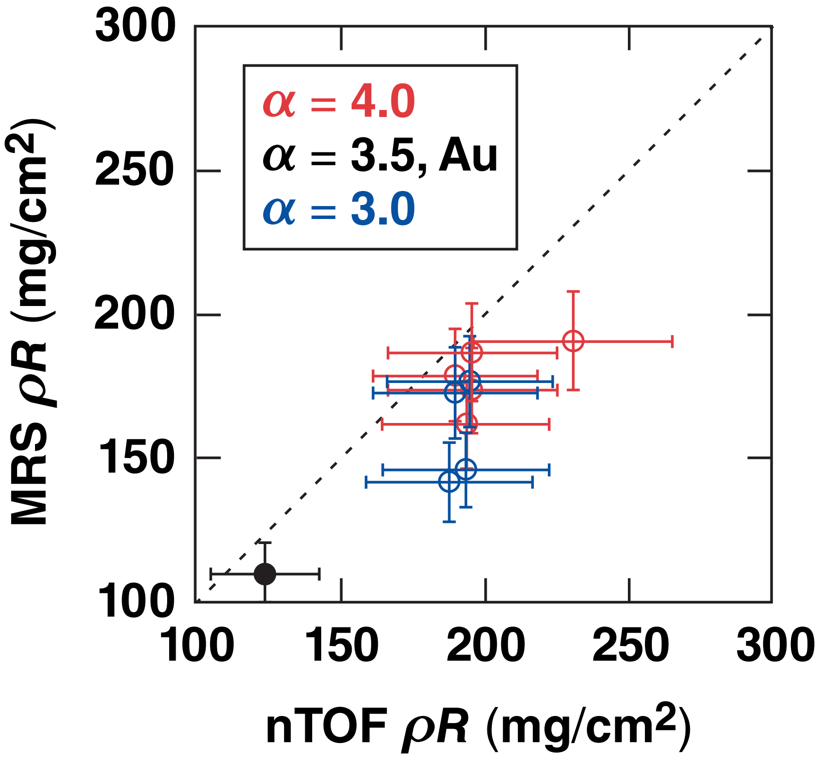
The measured neutron burnwidth is comparable to the 1-D prediction for the higher-adiabat implosions



The measured neutron burnwidth is consistent with the measured x-ray burnwidth.

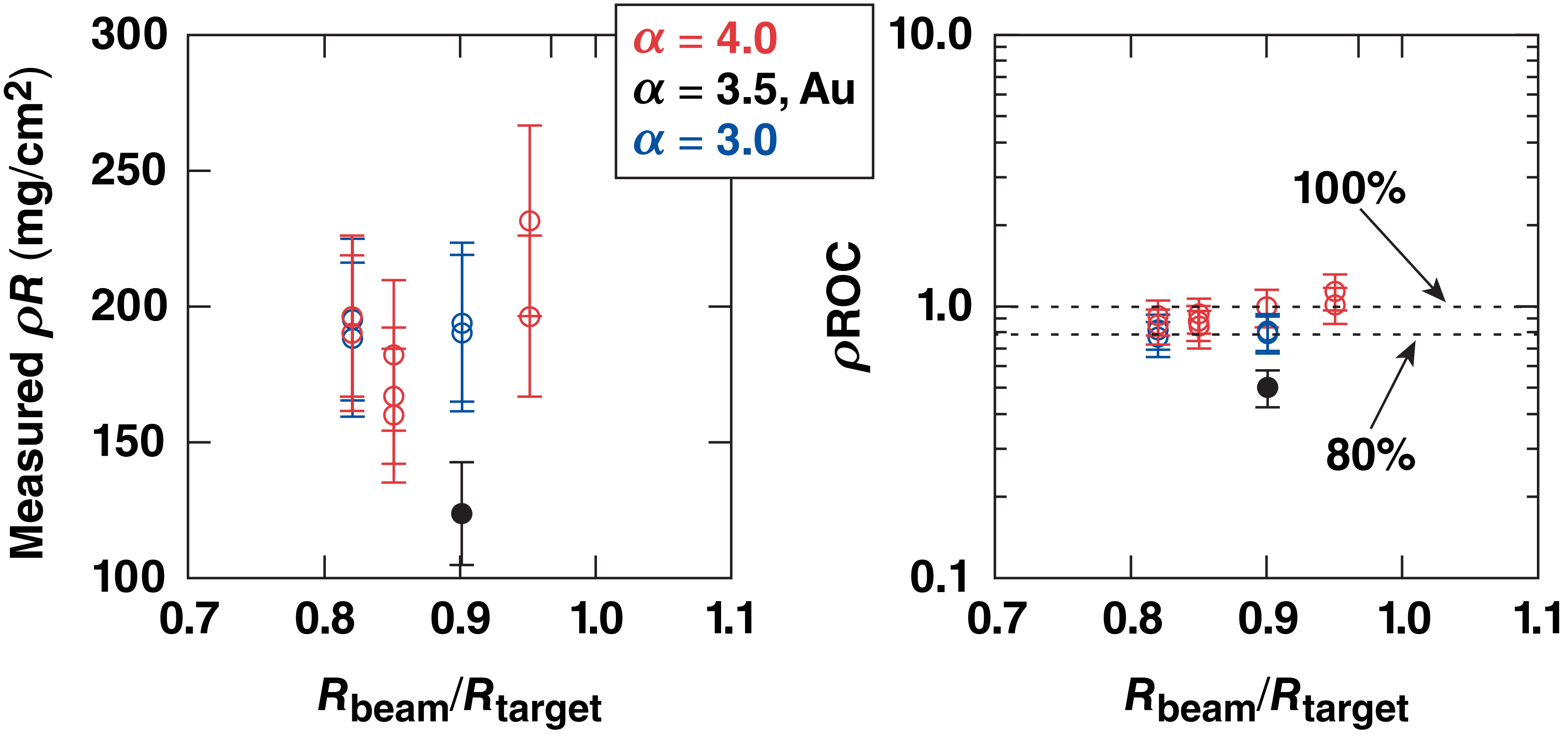
The MRS infers a slightly lower ρR than the nTOF



The comparison is sensitive to spatial variations of ρR since each diagnostic has a different line of sight.

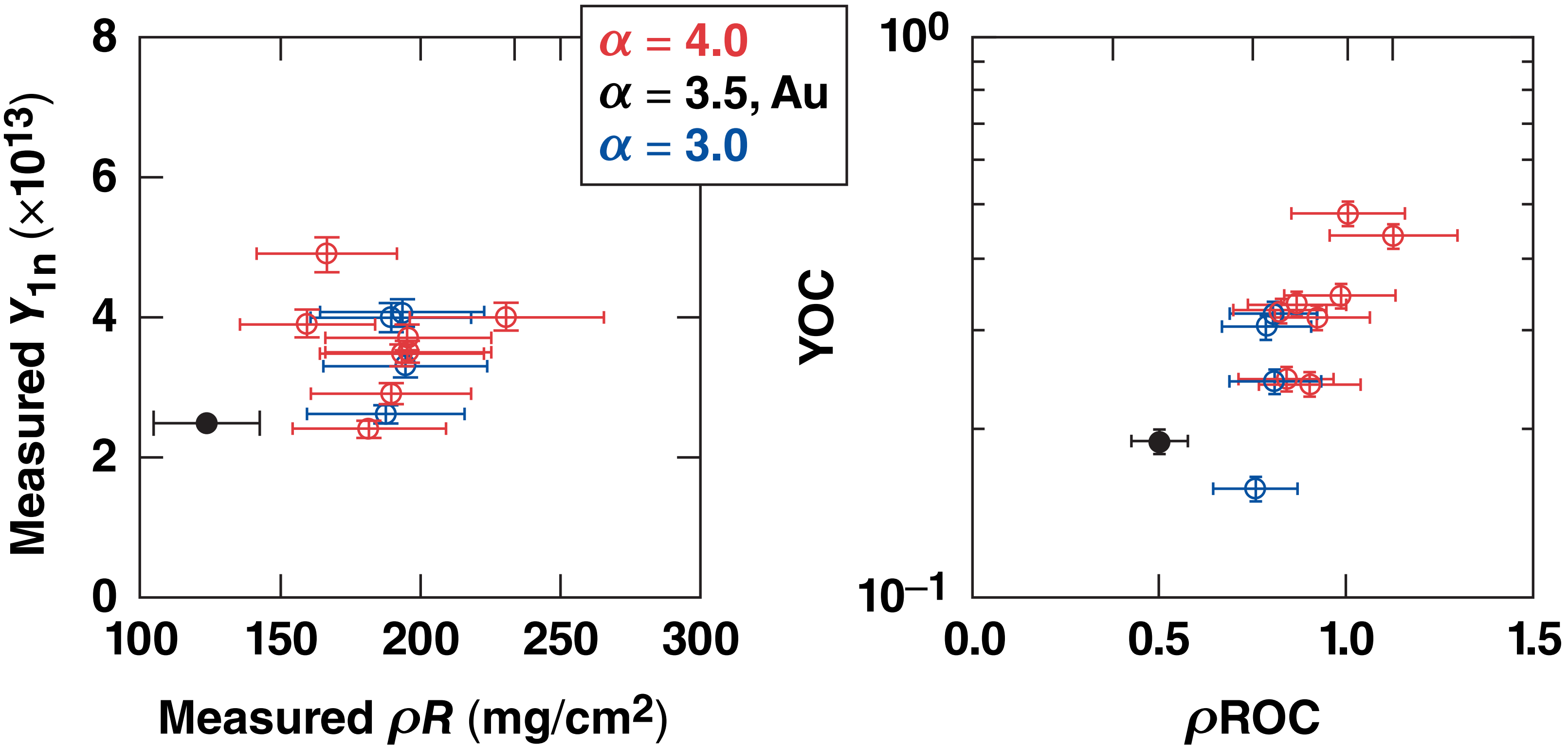
ρROC weakly depends on $R_{\text{beam}}/R_{\text{target}}$

$$\rho\text{ROC} = \frac{\rho R_{\text{expt}}}{\rho R_{\text{1-D}}}$$



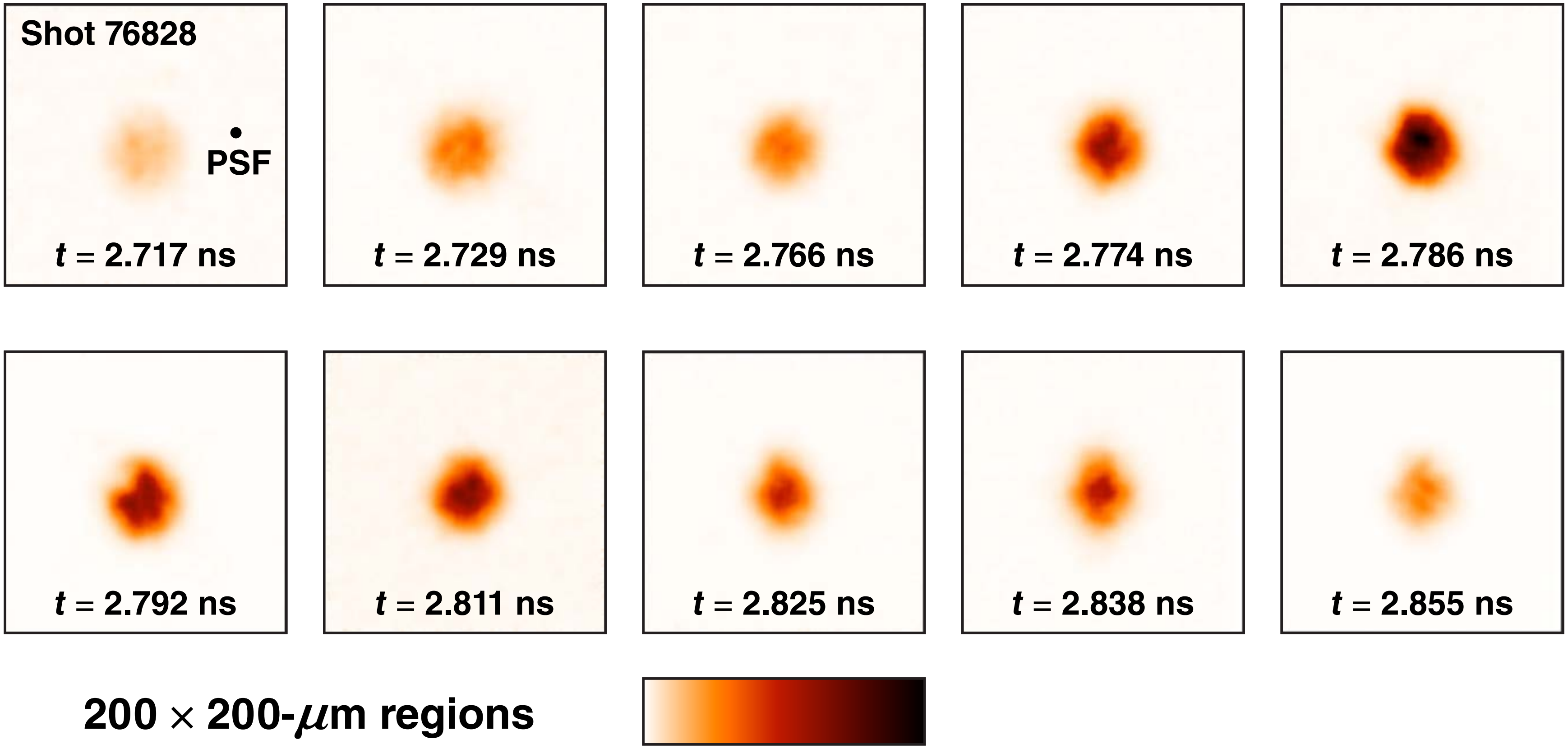
This indicates a low level of preheat.

Long-wavelength perturbations caused by beam geometry degrades yield but not *ρR*



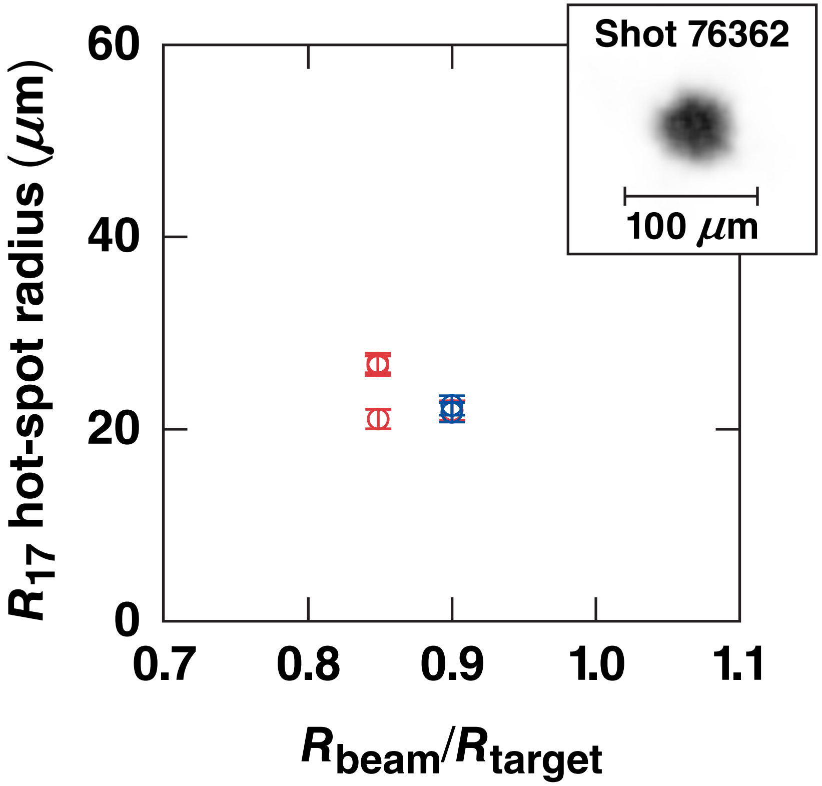
Better peformance is observed for the higher-adiabat implosions.

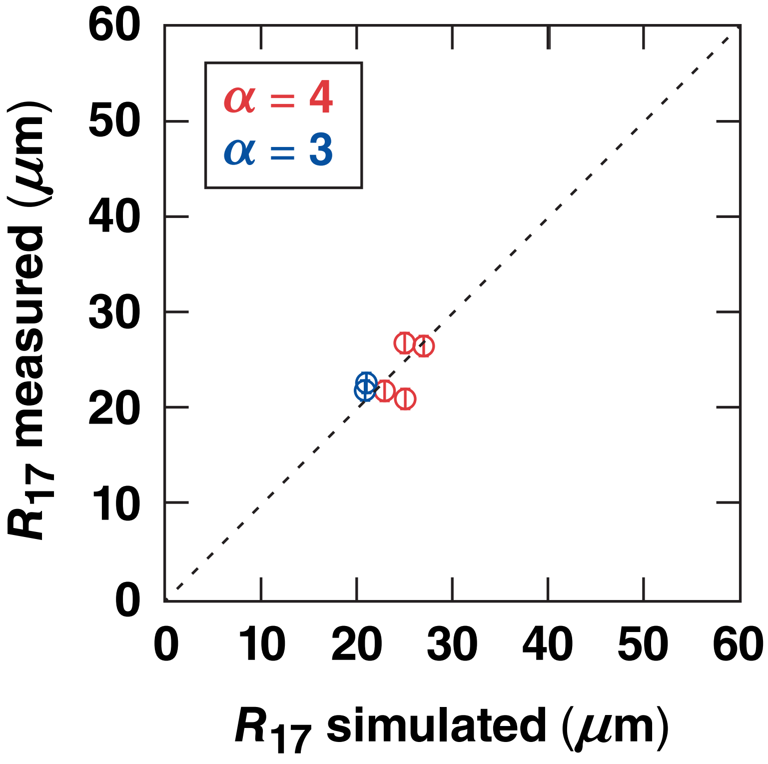
KBframed records an image (Δt = 30 ps) of the stagnating core every ~15 ps in the 4- to 8-keV photon energy range



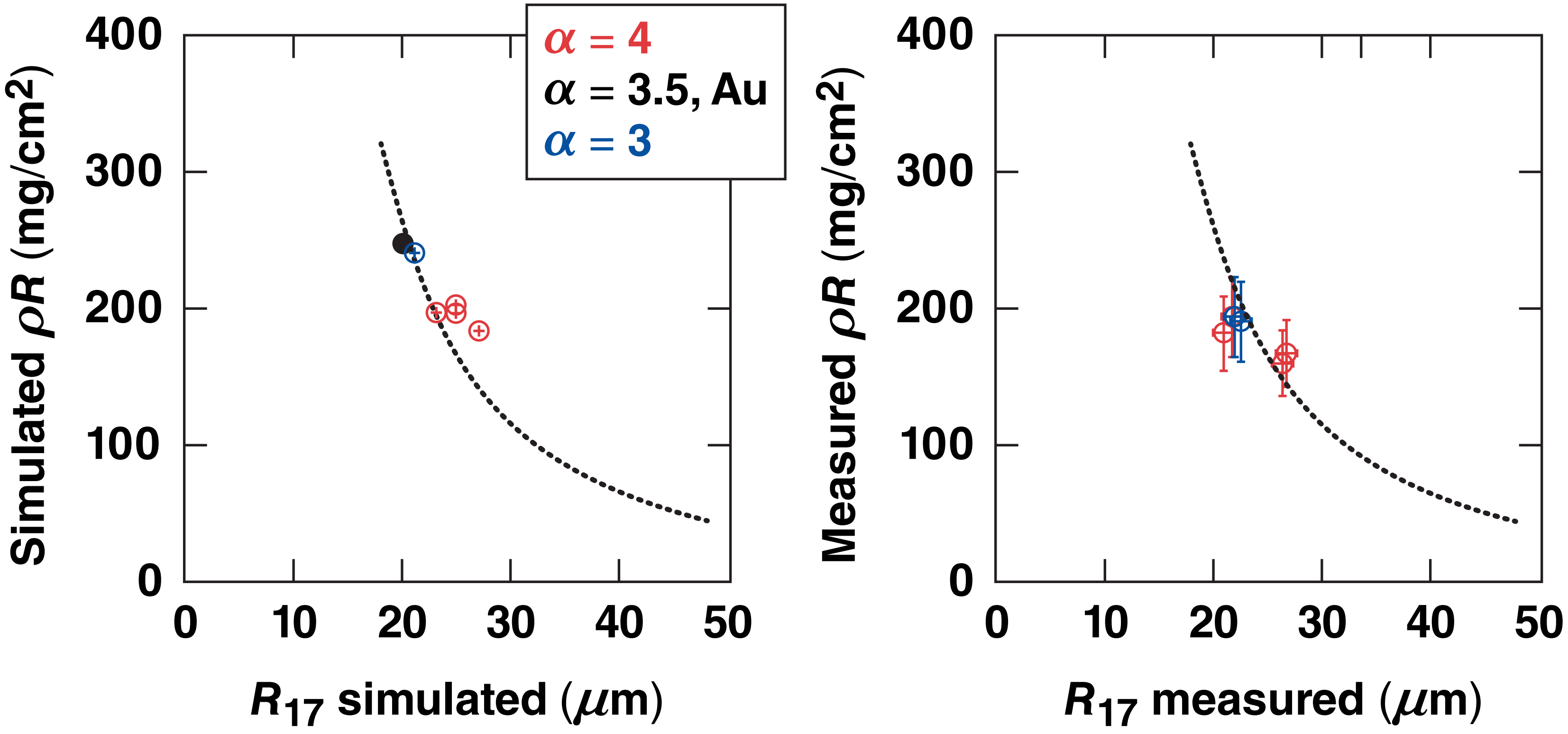
200 × 200-μm regions

The hot-spot radius decreases with increasing $R_{\text{beam}}/R_{\text{target}}$ and is comparable to the 1-D prediction

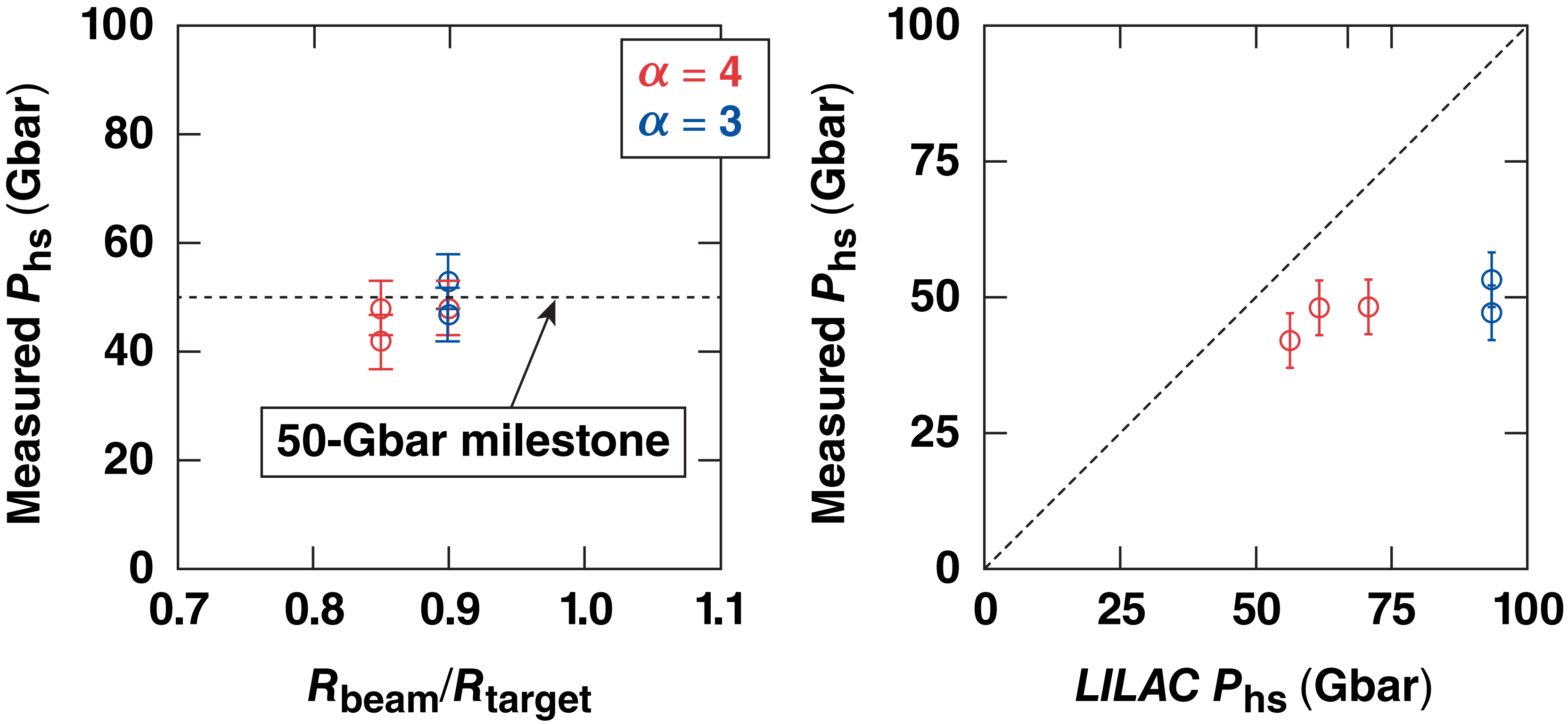




The measured ρR is consistent with the hot-spot size inferred from x-ray imaging

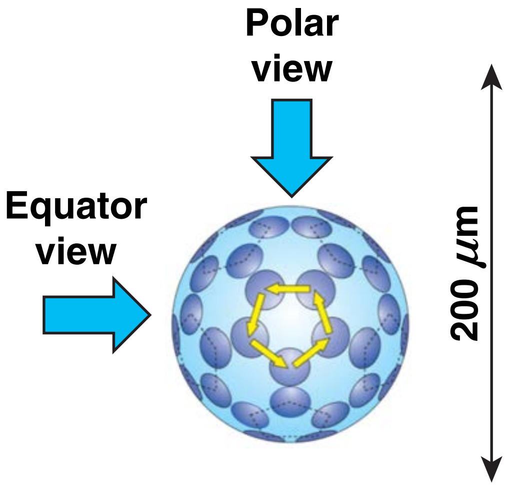


A 50-Gbar hot-spot pressure is inferred for layered DT cryogenic implosions on OMEGA



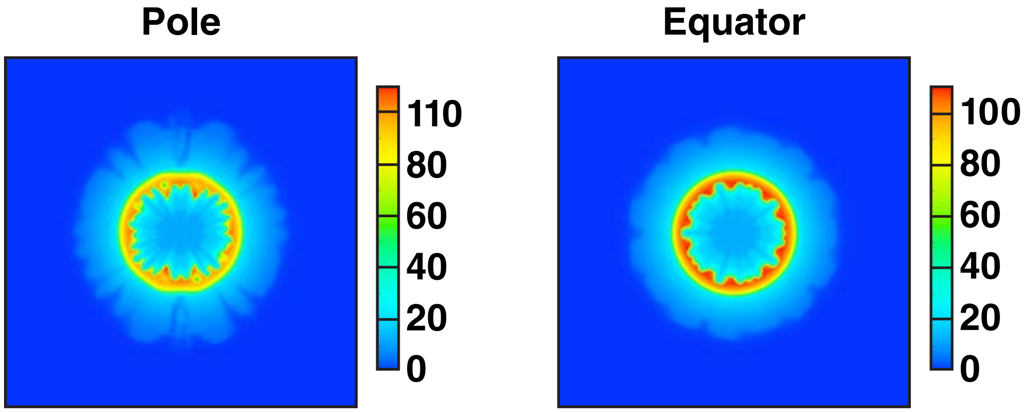
The results are preliminary.

Simulations indicate the target performance of the larger targets is degraded by the enhanced long-wavelength nonuniformity

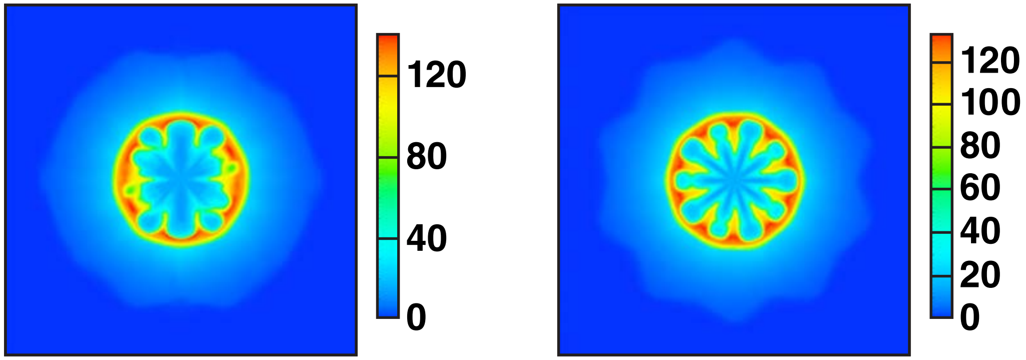


Peak neutron production, density contours, 3-D simulations

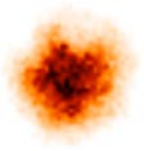
R_{target} = 430 μm, YOC = 86%



R_{target} = 500 μm, YOC = 67%



X-ray image at
peak neutron production
R_{target} = 480 μm



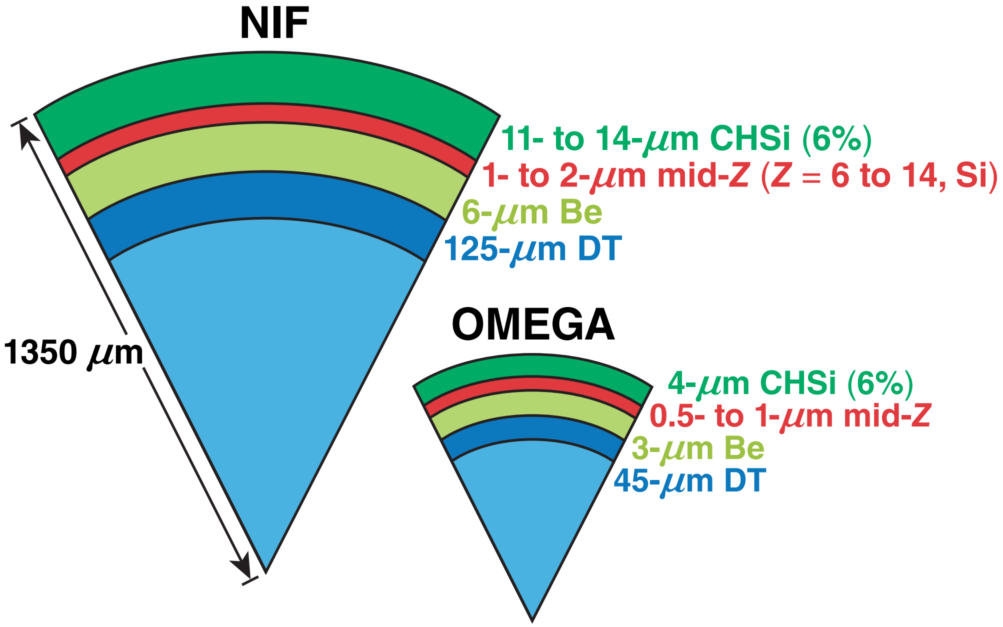
Outline

OMEGA layered DT cryogenic implosions

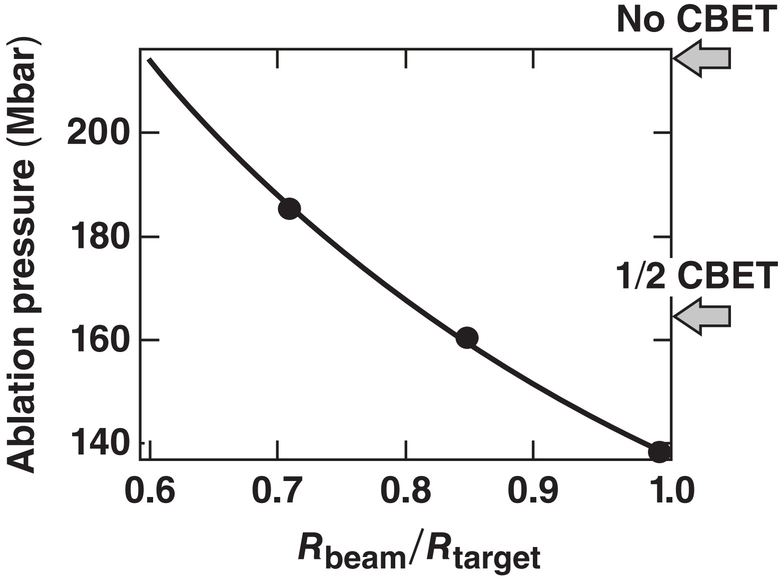
- Theory
  - CBET
  - hot-spot pressure
- Experiment
  - layered DT cryogenic targets
  - laser
  - diagnostics
- CBET mitigation campaign
  - $R_{\text{beam}}/R_{\text{target}}$ scan
- **Path to 100 Gbar**

Multilayer ablators and zooming are planned to increase the hot-spot pressure to 100 Gbar*

Multilayer ablators*



Zooming*



Multilayer ablators and zooming are designed to increase energy coupling, and reduce preheat and laser imprint.

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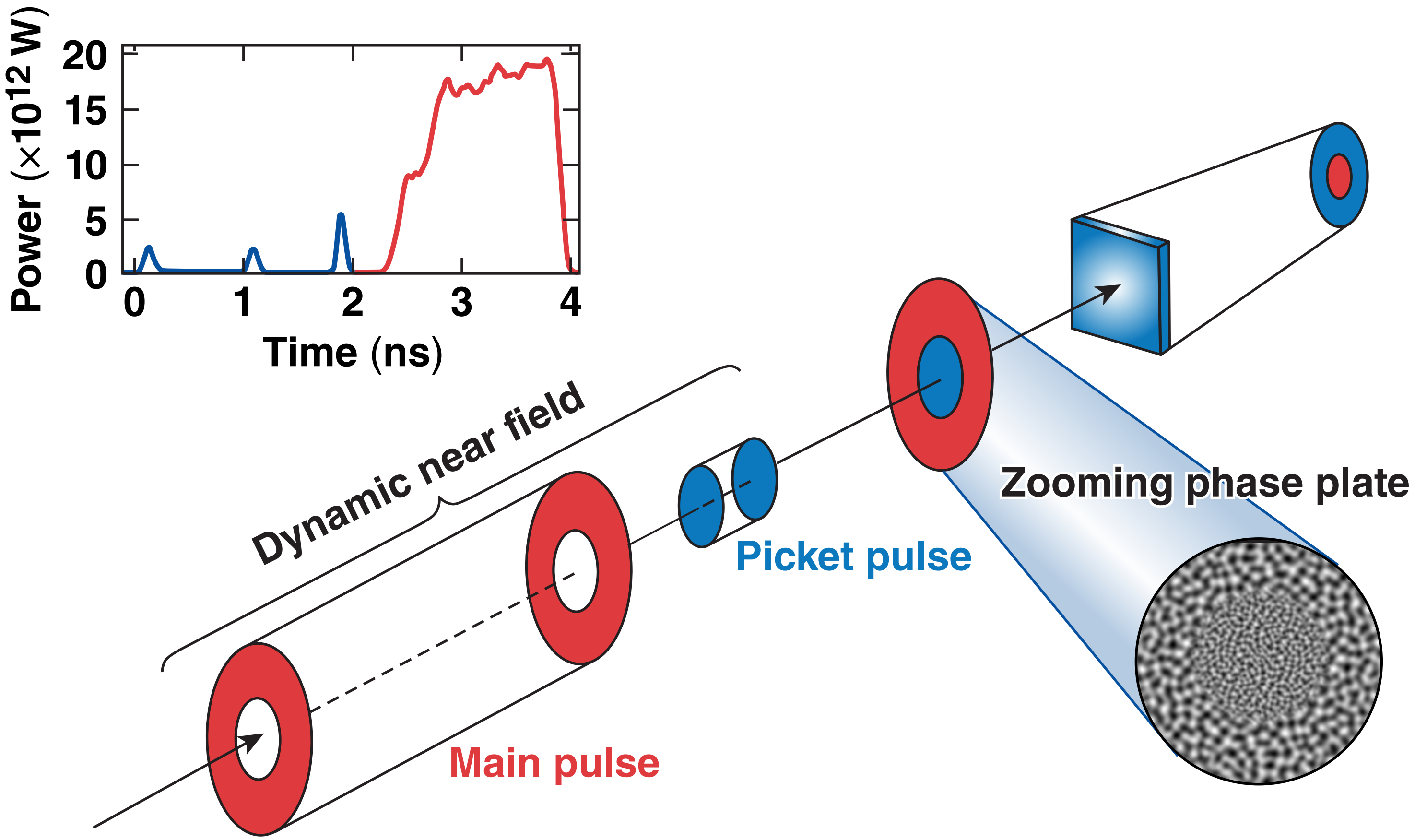
*V. N. Goncharov *et al*., Phys. Plasmas 21, 056315 (2014).

Near-Term Plan

A zooming phase plate (ZPP) is being developed to provide co-axial zooming on OMEGA



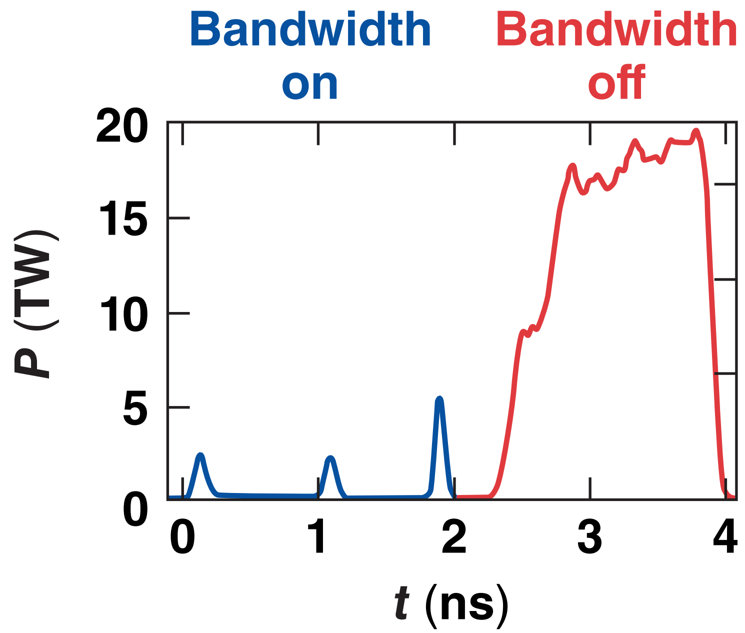
The picket portion of the laser pulse has a larger spot size on target compared to the main drive.

D. H. Froula *et al.*, Phys. Plasmas 20, 082704 (2013).

Long-Term Plan

More laser energy can be coupled to the target with full-aperture zooming compared to co-axial zooming

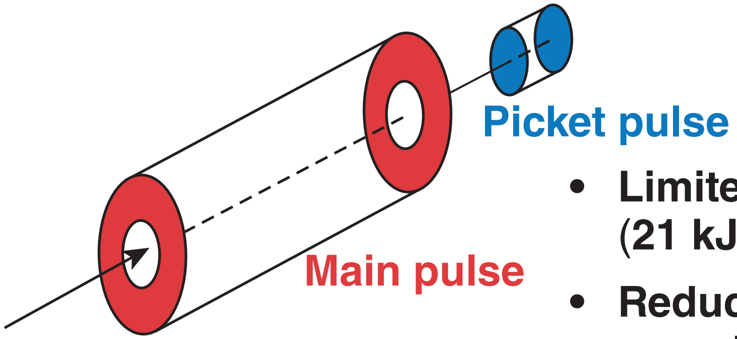
Dynamic bandwidth reduction



The concept for full-aperture zooming on OMEGA is under development.

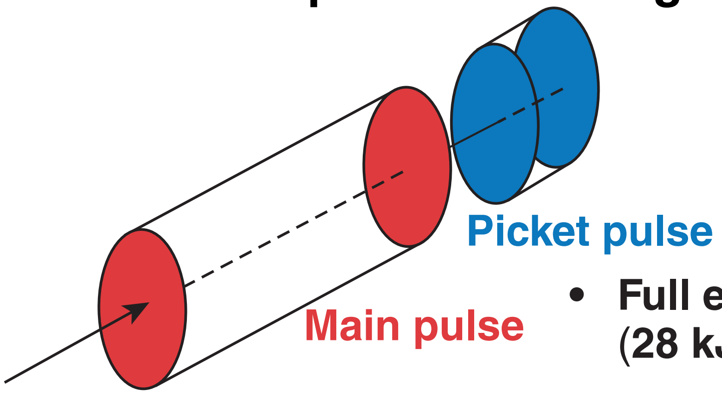
Dynamic near field

Coaxial zooming



- Limited energy (21 kJ)
- Reduced smoothing

Full-aperture zooming



- Full energy (28 kJ)
- Enhanced smoothing

Summary/Conclusions

Hot-spot pressure is a key performance metric for layered DT cryogenic implosions on OMEGA*

- Cross-beam energy transfer (CBET) reduces the ablation pressure of direct-drive inertial confinement fusion (ICF) targets**
- A CBET mitigation campaign is underway on OMEGA
  - $R_{\mathrm{beam}}/R_{\mathrm{target}}$ scan
  - SG5 phase plates
  - multipulse driver with dynamic bandwidth reduction
- PRELIMINARY: hot-spot pressure of 50 Gbar has been diagnosed
  - hot-spot size: 16-channel Kirkpatrick–Baez gated imager (KBframed)
  - neutron burnwidth: P11 neutron temporal diagnostic (P11-NTD)

An ignition-relevant hot-spot pressure of 100 Gbar will be pursued on OMEGA using beam zooming and multi-ablator targets.

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*V. N. Goncharov *et al*., Phys. Plasmas 21, 056315 (2014);
R. Nora *et al*., Phys. Plasmas 21, 056316 (2014);
C. Cerjan, P. T. Springer, and S. M. Sepke, Phys. Plasmas 20, 056319 (2013).

**I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).