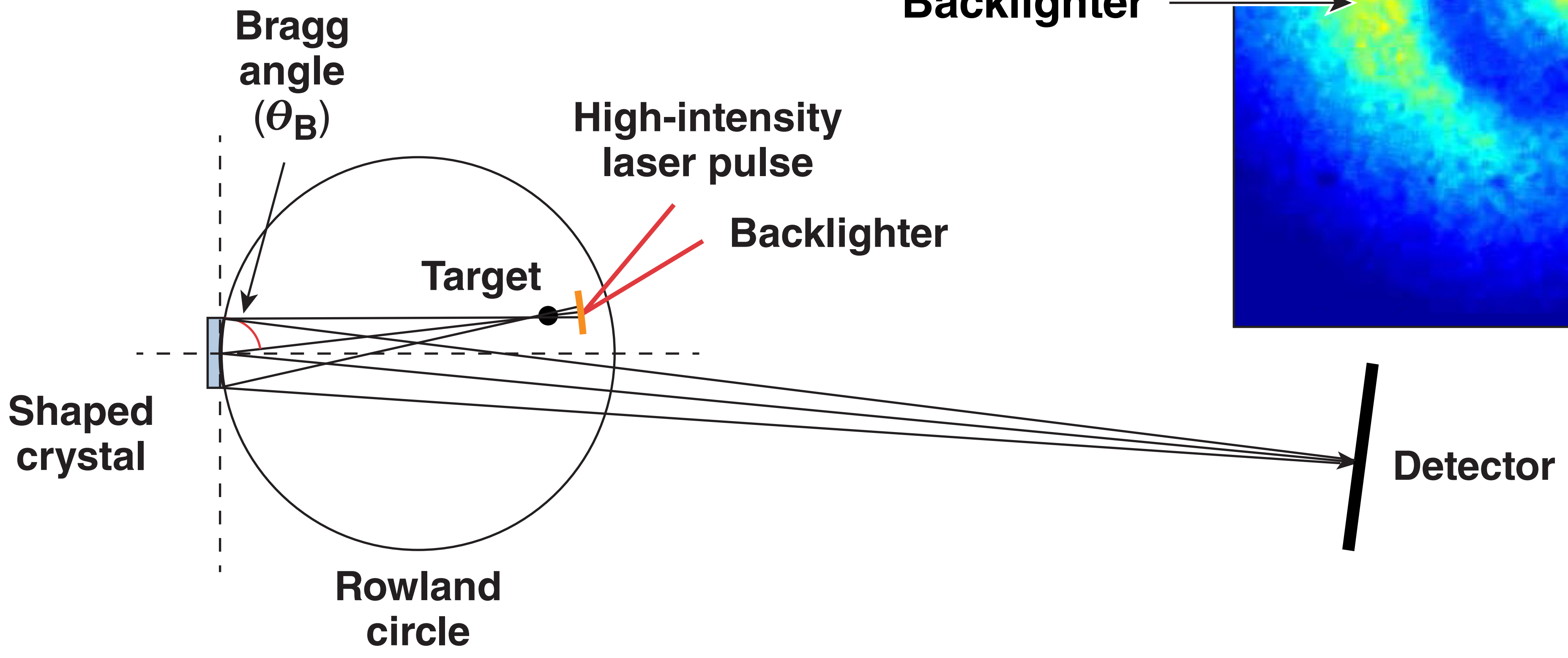
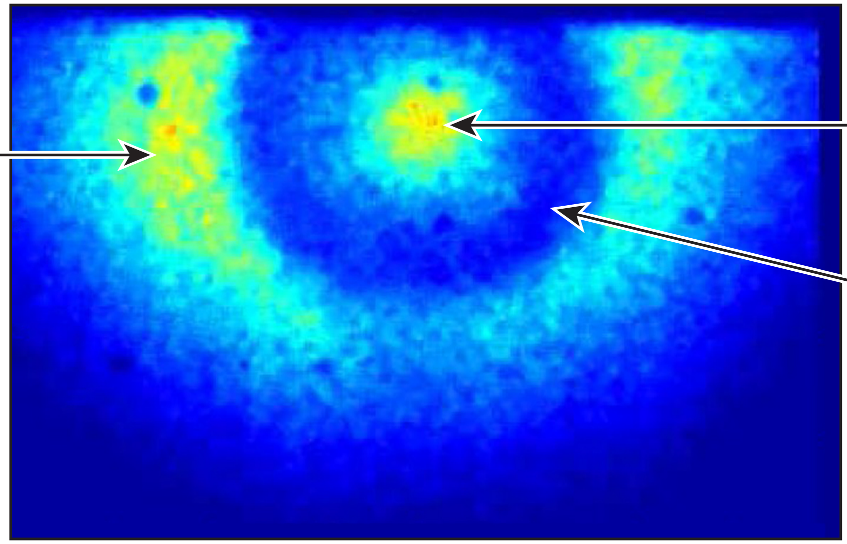
Monochromatic Backlighting of Direct-Drive Cryogenic DT Implosions on OMEGA





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The effects of perturbations on direct-drive DT cryogenic implosions are diagnosed with monochromatic x-ray backlighting

- A crystal imager* is used for short pulse (20 ps), monochromatic x-ray backlighting** (1.865 keV) of 60-beam OMEGA DT cryogenic implosions
- Low-mode nonuniformities have been studied† close to stagnation in experiments with pre-imposed shell-thickness variations
- The effects of localized perturbations like the target stalk have been observed with both mass-equivalent CH and DT cryogenic targets
- The level of mixing of plastic ablator with the DT ice has been inferred at in-flight aspect ratios (IFAR's) ~ 20 and adiabats from 2.5 to 4.0

All three sources of perturbations contribute to the performance degradation observed in the experiments.

*C. Stoeckl *et al*., Rev. Sci. Instrum. 85, 11E501 (2014).
**R. Epstein *et al*., TO5.00005, this conference.
†I. V. Igumenshchev, CI3.00002, this conference (invited).

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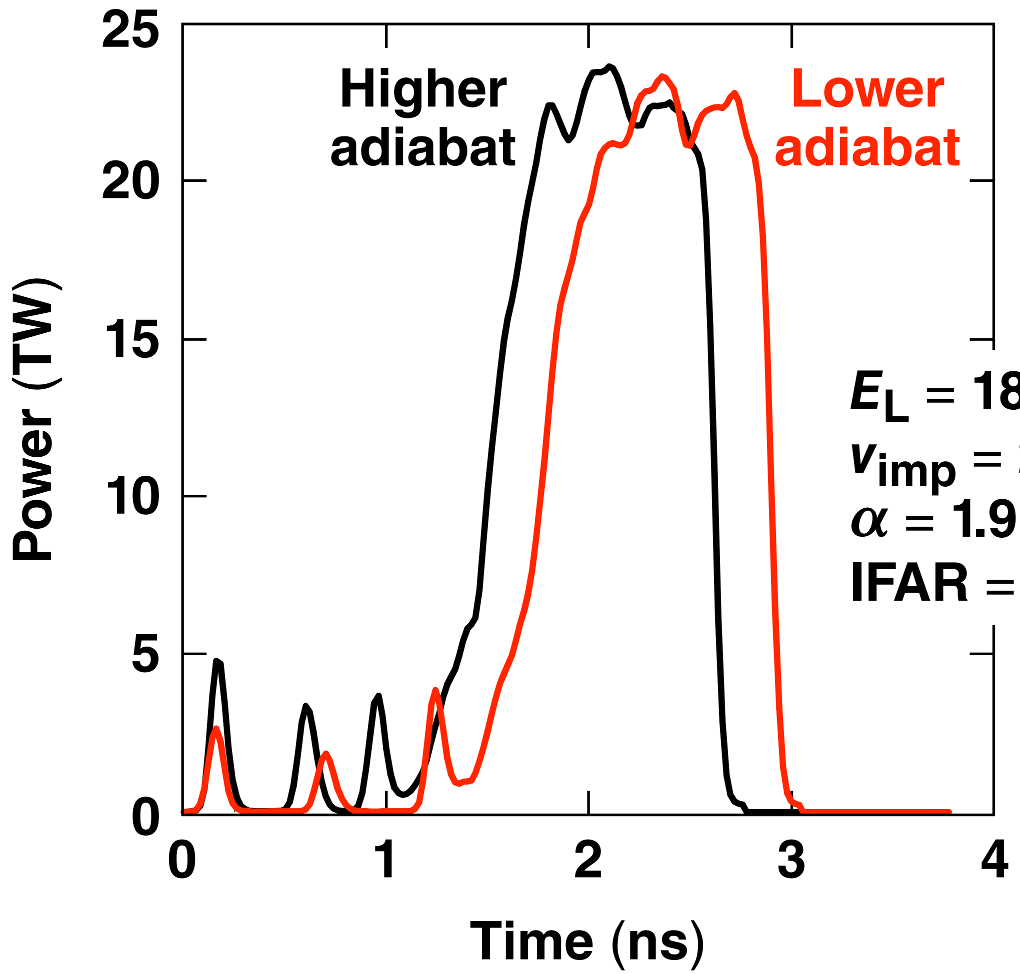
Outline

- **Motivation**
- Experimental setup
- Low modes
- Imprint and mix
- Localized perturbations

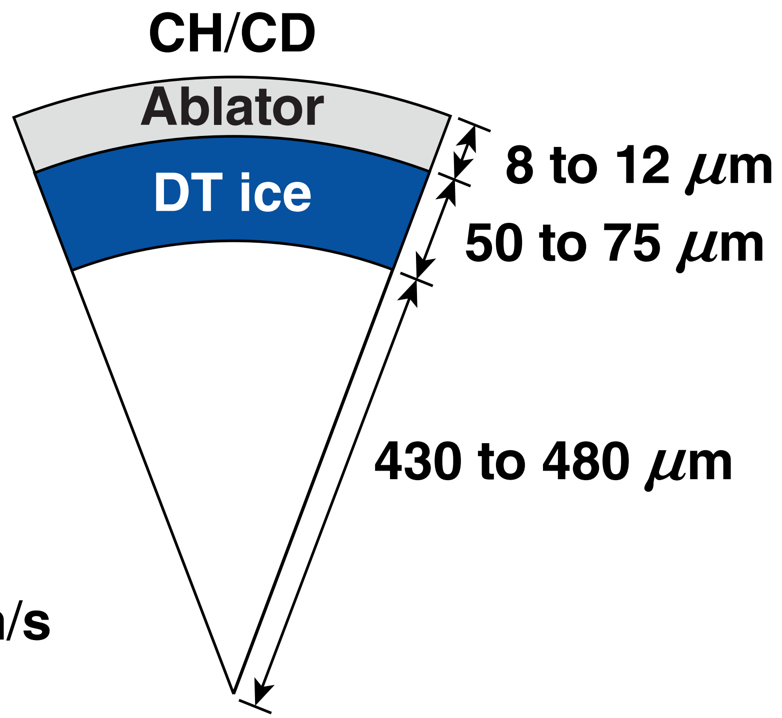
E25670

The expected target performance is determined by the laser pulse shape and the target dimensions

Adiabat and IFAR are controlled by pulse shaping



E_L = 18 to 25 kJ
v_{imp} = 2.4 to 3.7 $\times$ 10^7 m/s
α = 1.9 to 4.3
IFAR = 10 to 20



- Adiabat $\alpha = P/P_{Fermi}$
- v_{imp} = Implosion velocity
- E_L = Laser energy
- IFAR = shell radius/shell thickness

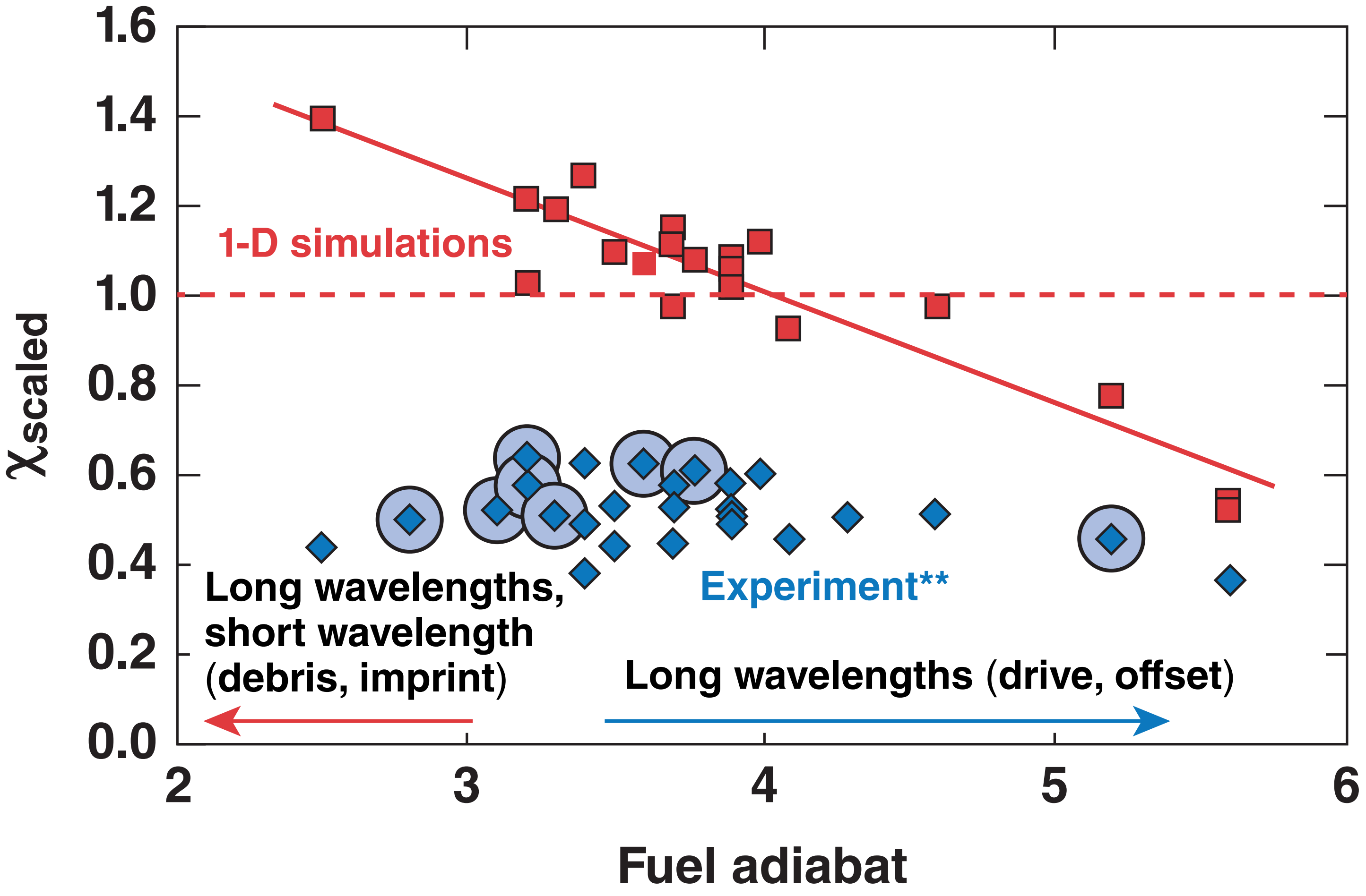
TC10248u

Simulations indicate that both short- and long-wavelength perturbations limit the target performance

UR LLE

Generalized Lawson criterion*

$$\chi_{\text{scaled}} = P\tau/P\tau_{\text{ign}} = (\rho R_{\text{no}\,\alpha})^{0.61}\left(0.12\,Y^{16}_{\text{no}\,\alpha}\big/M^{\text{stag}}_{\text{DT}}\right)^{0.34}\left(E^{\text{NIF}}_{\text{laser}}\big/E^{\text{OMEGA}}_{\text{laser}}\right)^{0.35}$$



Shot with inferred P_{hs} > 50 Gbar

Image from NNSA framework document

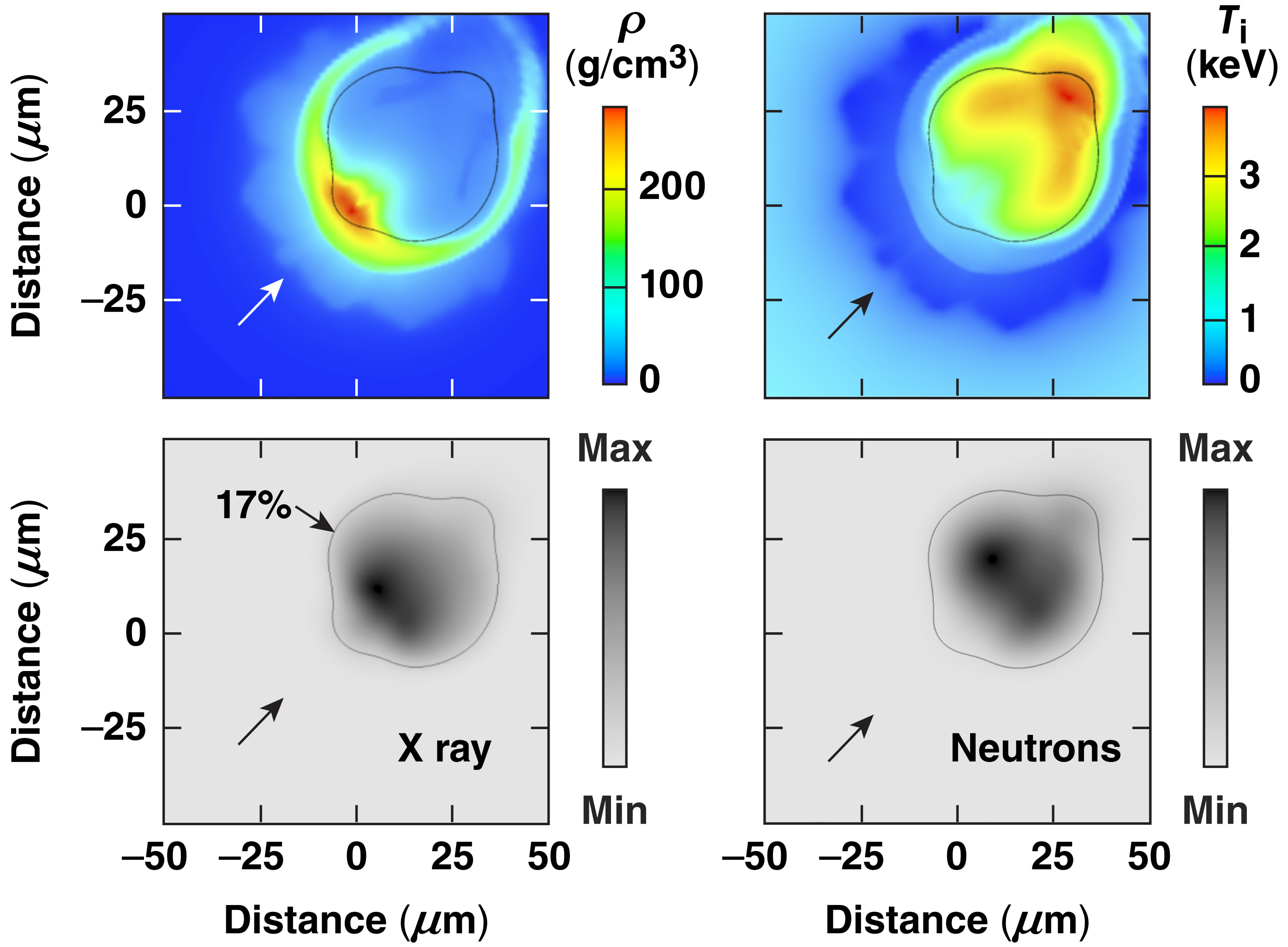
*R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015);
A. Bose *et al.*, Phys. Rev. Lett. E 94, 011201(R) (2016).

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

E25536a

The x-ray or neutron images of the hot spot do not reflect the shape of the dense shell

***ASTER** 3-D simulations*



Peak neutron production t = 2.57 ns

Sources

- 20-μm offset
- Beam overlap
- 10% imbalance
- 10-μm-rms mispointing
- 5-ps-rms mistiming

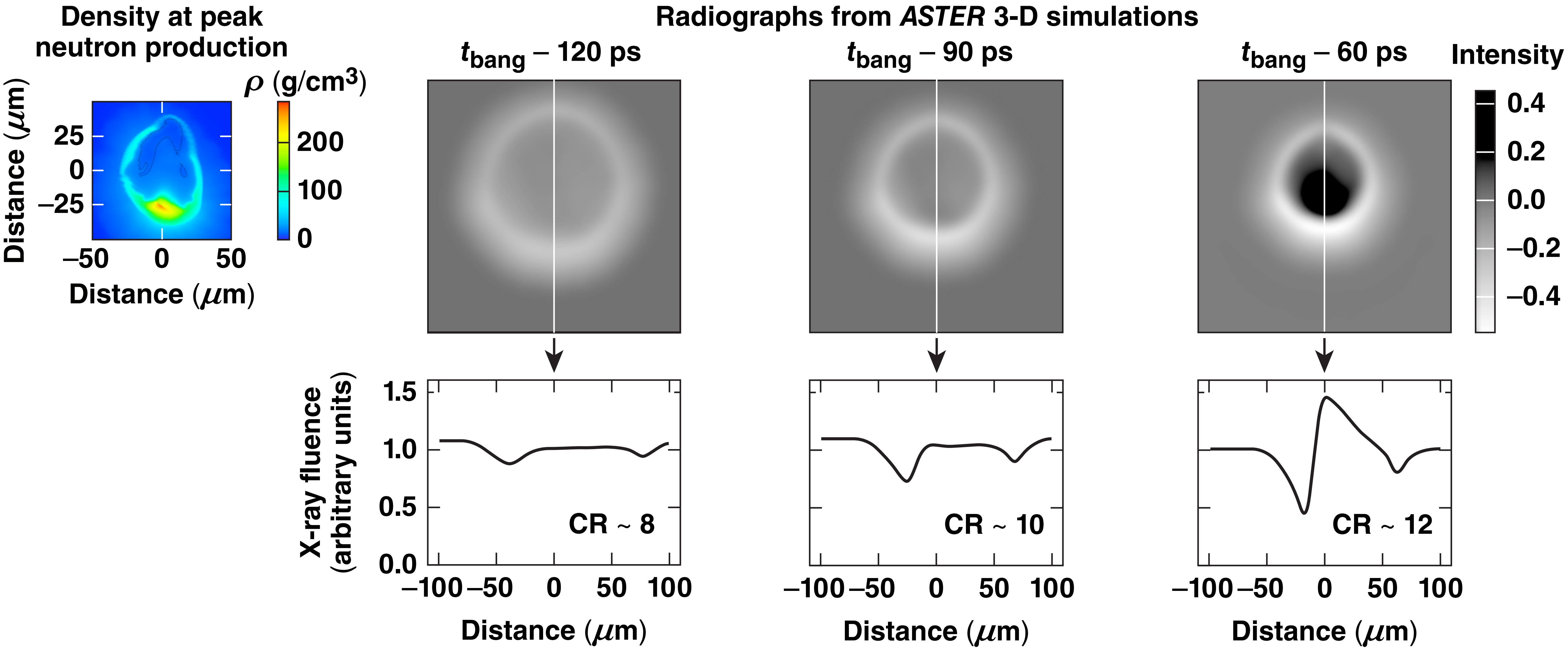
The goal of monochromatic backlighting is to radiograph the compressed shell close to peak compression.

rms: root mean square

*I. V. Igumenshchev, CI3.00002, this conference (invited); I. V. Igumenshchev *et al*., Phys. Plasmas 23, 052702 (2016).

TC12513b

The nonuniformities in the target evolve significantly in the 100 ps before peak neutron production



CR: convergence ratio

E25721

Outline

- Motivation
- **Experimental setup**
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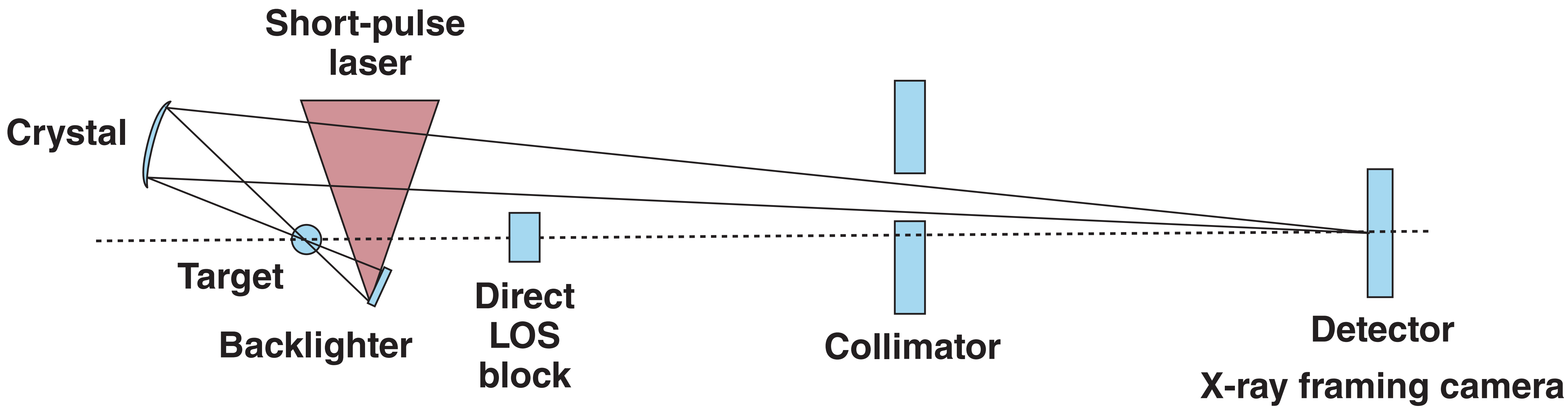
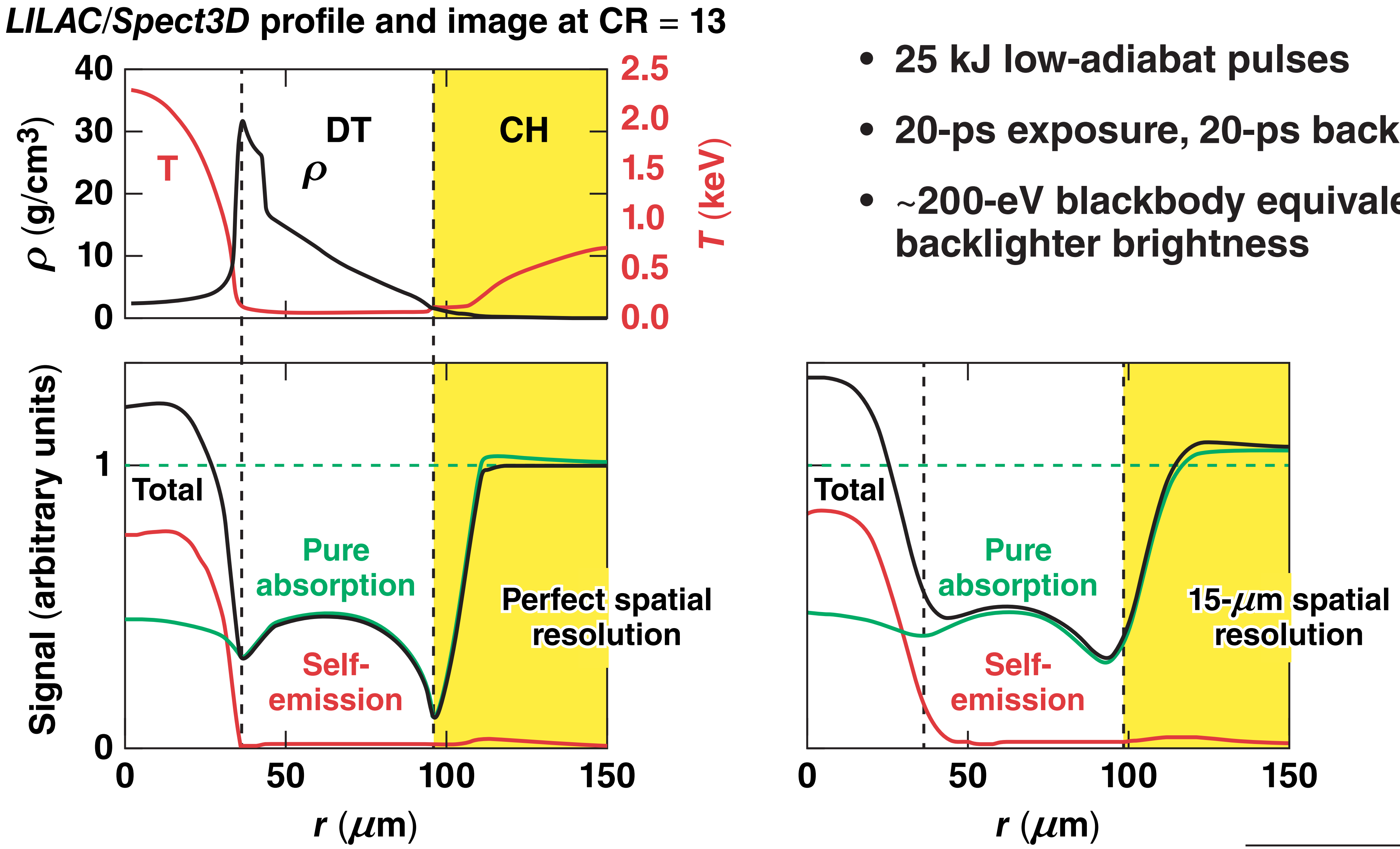
Monochromatic backlit images of DT cryo implosions are recorded with a shaped Bragg crystal-imaging system



- The backlighter foil is not in the focus of the imaging system, so the backlighter uniformity does not depend on the laser-intensity distribution
- A collimator blocks the line of sight (LOS) to the backlighter, minimizing the background from the short-pulse laser
- A direct LOS block shields the detector from background produced by the implosion target

E20916d

Better spatial resolution and a higher brightness of the backlighter will improve the performance of the radiography setup*



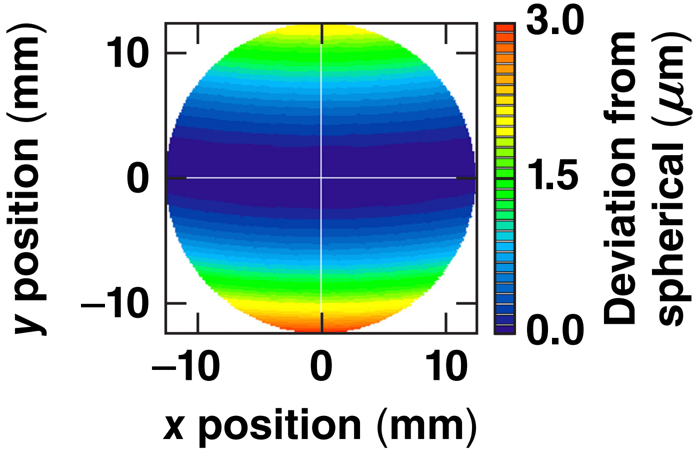
- 25 kJ low-adiabat pulses
- 20-ps exposure, 20-ps backlighter
- ~200-eV blackbody equivalent backlighter brightness

*R. Epstein *et al.*, TO5.00005, this conference.

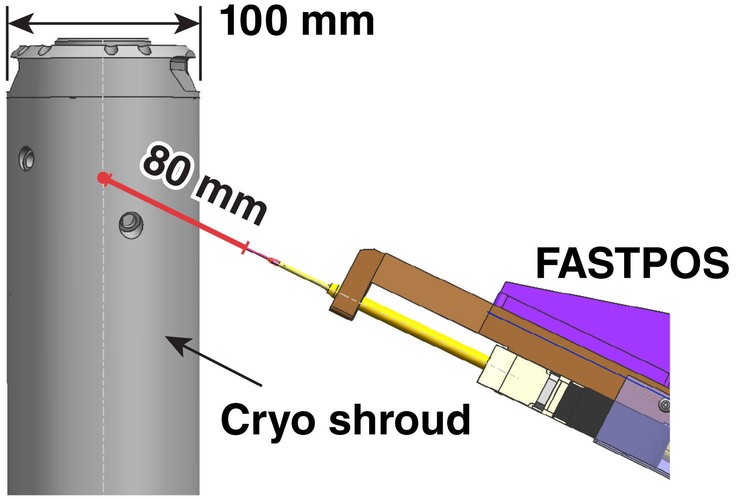
TC13002b

Three key innovations were required to make it possible to field a crystal-imaging system on cryogenic shots

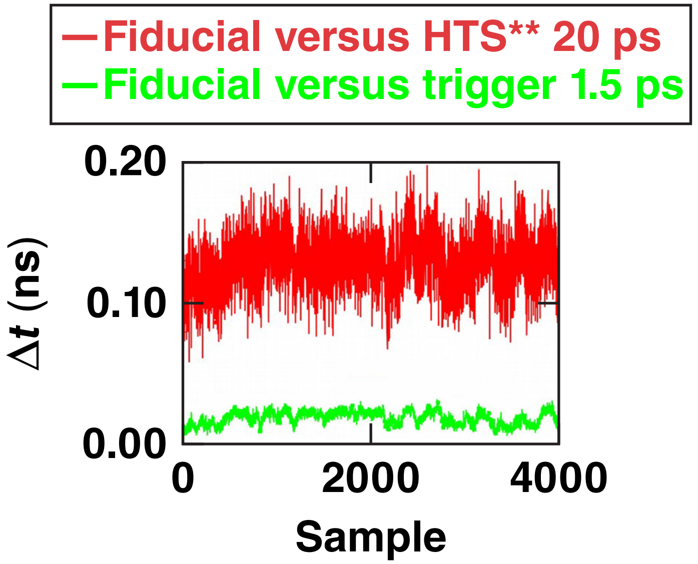
- An aspherically shaped substrate was designed* to reduce the optical aberration of the imager at the relative large angle of incidence of 6.2°



- A fast target-insertion system* positions the backlighter target within ~100 ms after the cryo shroud has been removed



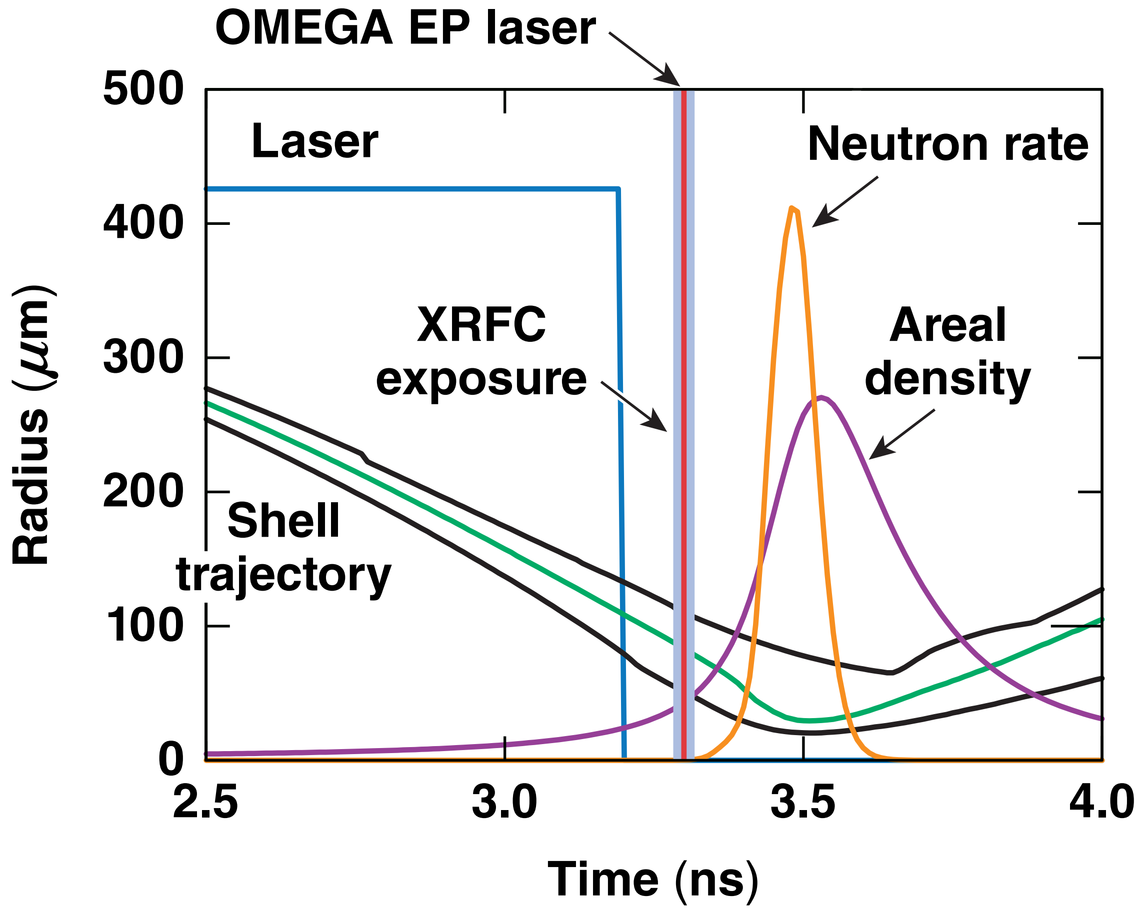
- An ultrastable optoelectronic trigger system with a jitter of ~1.5-ps rms triggers the 40-ps exposure time framing-camera detector

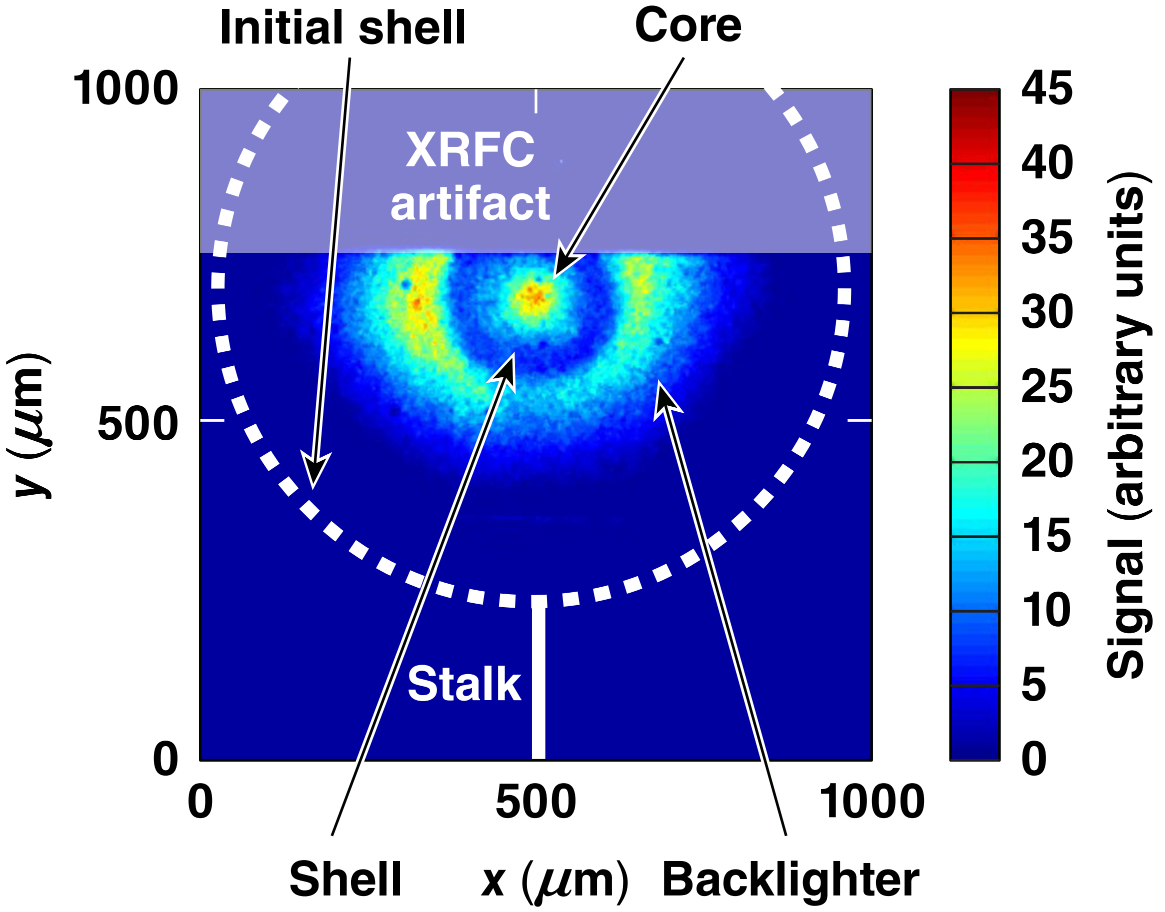


*C. Stoeckl *et al*., Rev. Sci. Instrum. 85, 11E501 (2014).
**HTS: hardware timing system

E25614

High-quality backlit images of the compressed DT shell were taken at CR ~7





The intensity profile of the backlighter must be removed to infer the absorption of the shell.*

XRFC: x-ray framing camera
*C. Stoeckl *et al*., Rev. Sci. Instrum. 20, 056317 (2013).

Outline

- Motivation
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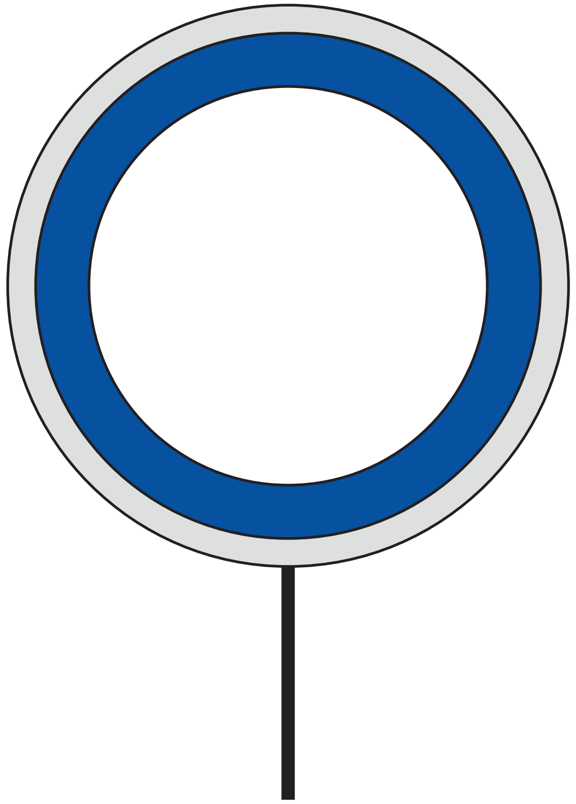
- Localized perturbations

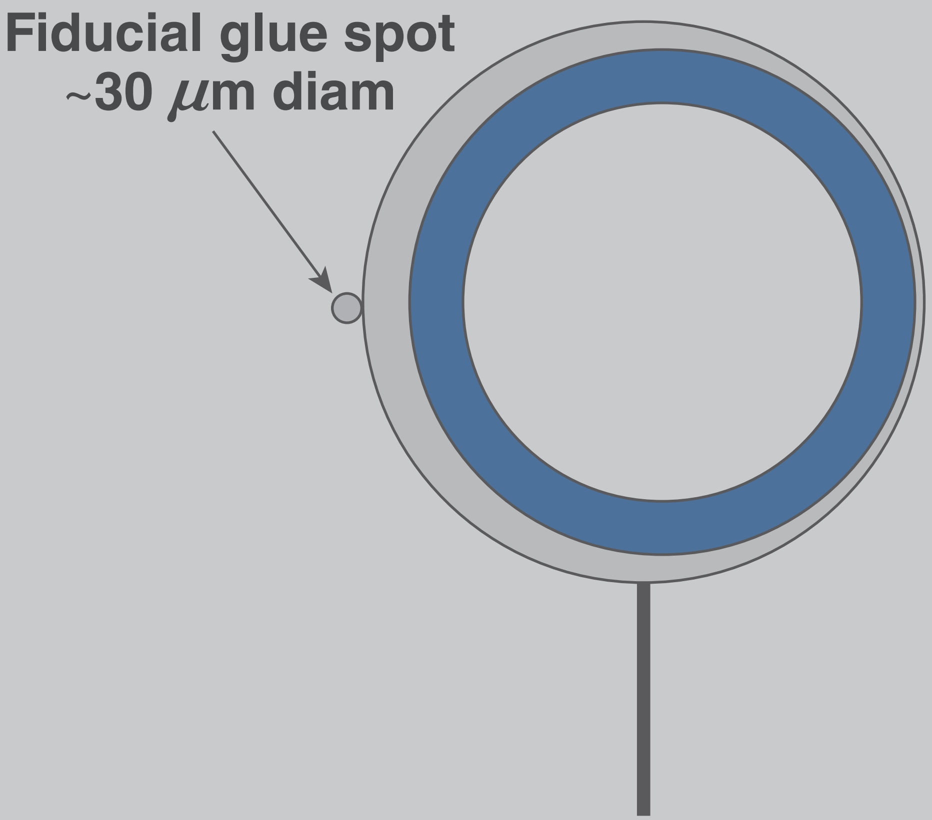
E25670b

The influence of low-mode nonuniformities was studied using targets with shell-thickness variations

Not to scale



- **Shell-thickness nonuniformity ~0.1-μm rms**
- **Ice-thickness nonuniformity <1-μm rms**

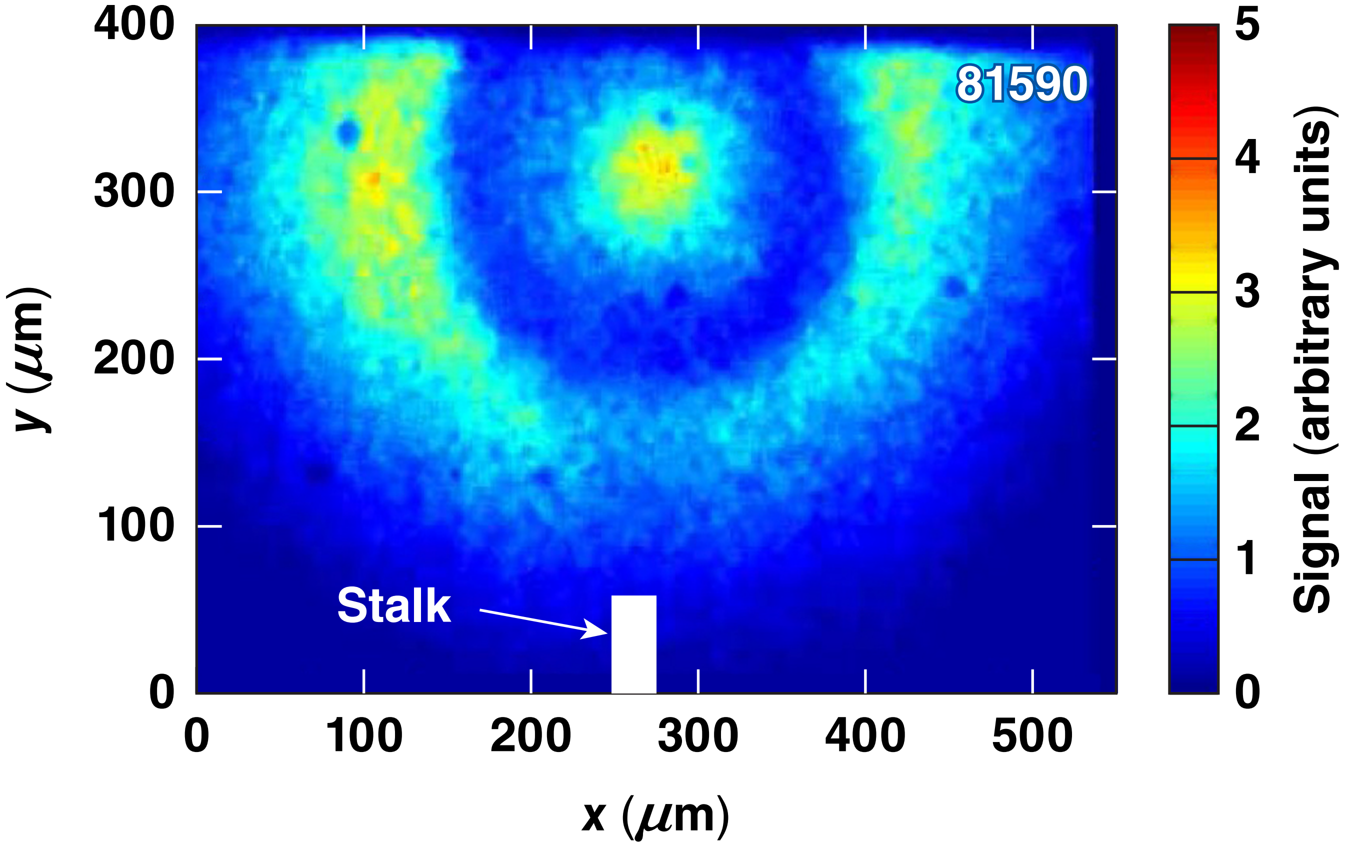


- **Shell-thickness nonuniformity 2- to 4-μm peak to peak**
- **Ice-thickness nonuniformity ~2-μm rms**

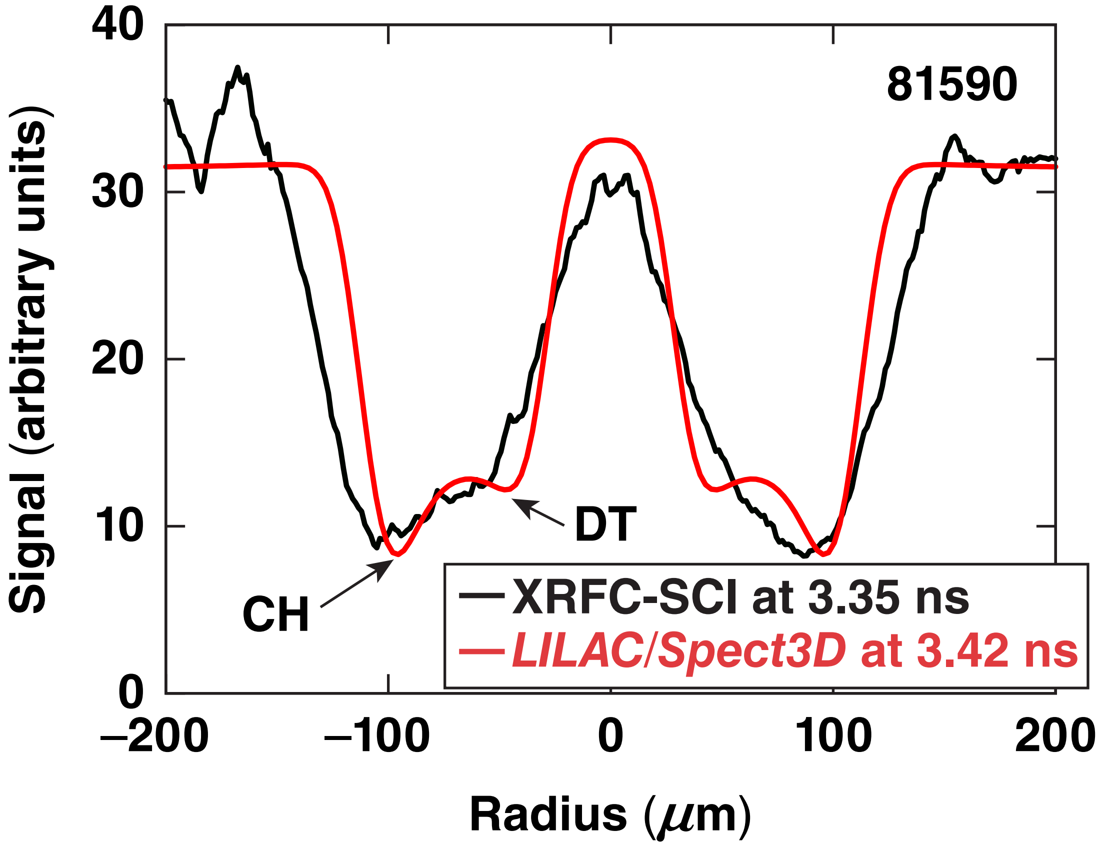
E25616a

Low-mode structure is seen in the radiograph at a CR of 7 for a uniform shell-thickness target

Experimental radiograph



Horizontal lineout + 1-D simulation

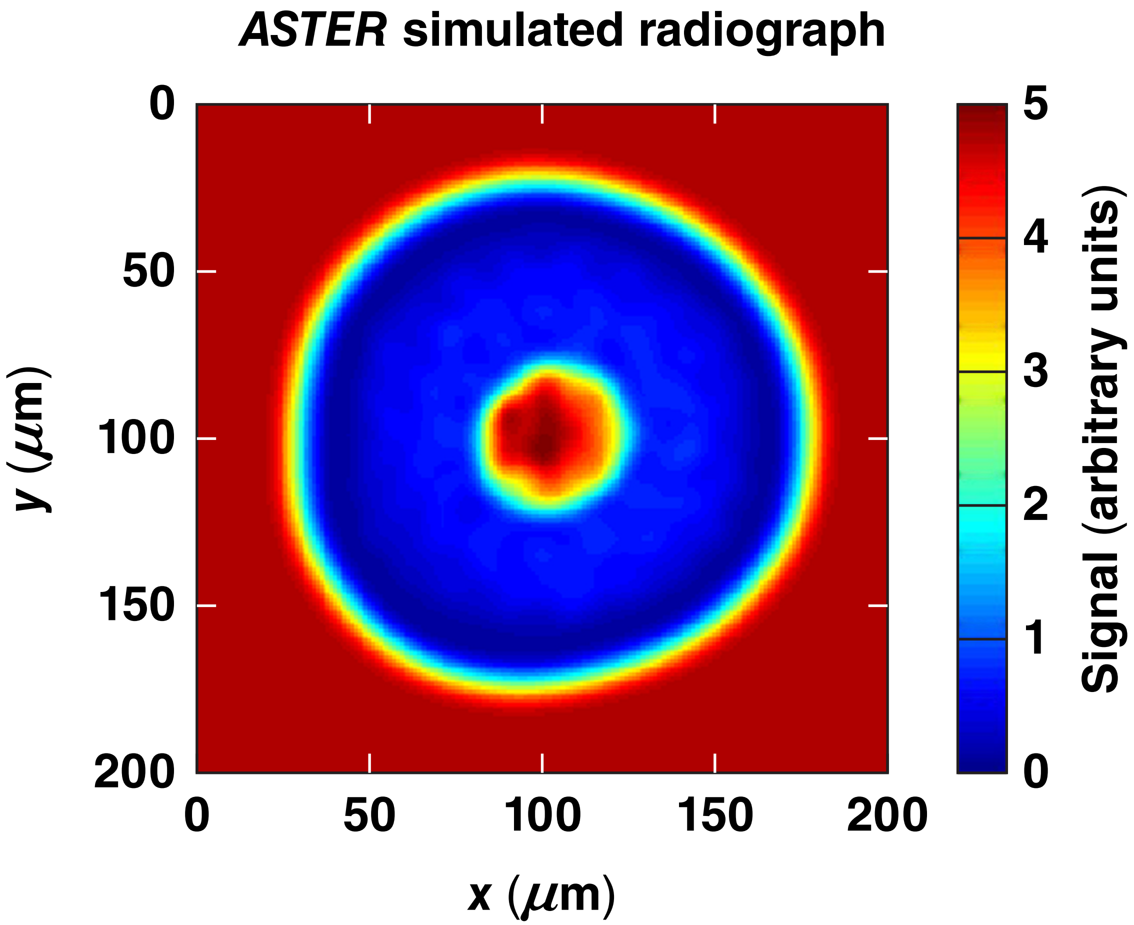


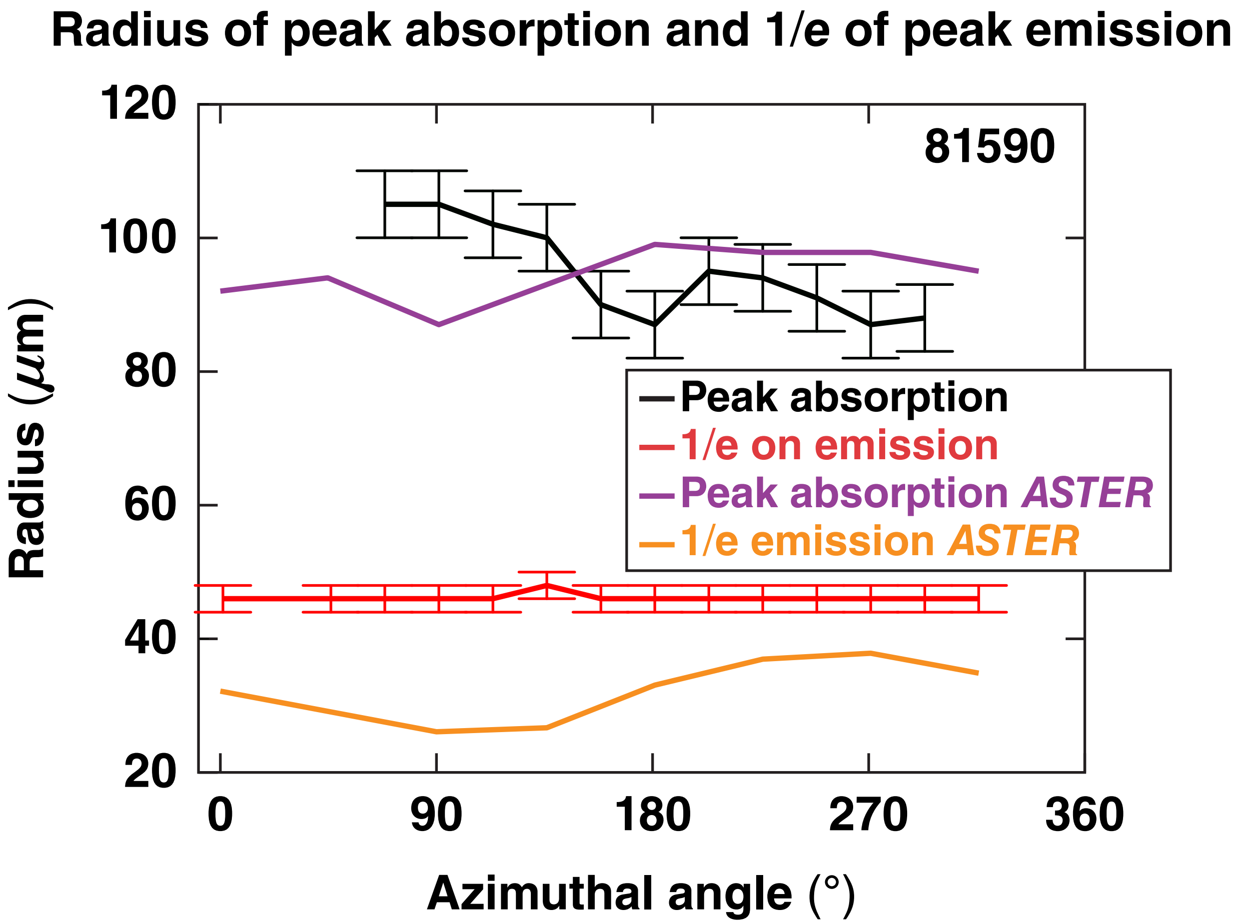
- Exposure time of 40 ps, ~100 ps before bang
- DT(60 μm) CH(12 μm), 888-μm diam, offset < 10 μm
- α = 2.5, IFAR ~10, YOC = 20%, ρR/clean = 78%

E25618

YOC: yield over clean

Both radius and magnitude of peak absorption show a variation as a function of azimuthal angle comparable to the simulations



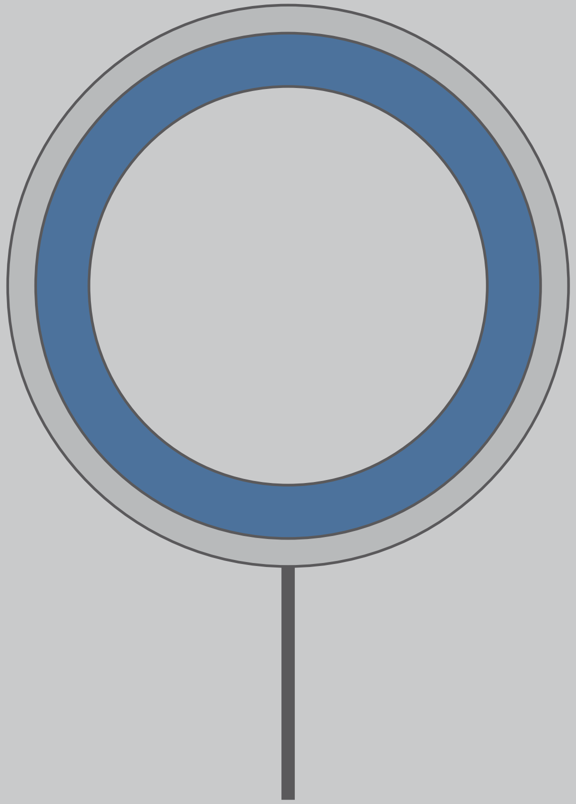


- An $\ell = 1$ of ~5 μm can be introduced by the choice of image center
- $\ell = 1$ with an amplitude of ~10 μm on the radius of peak absorption
- All low-mode effects accounted for in the simulation; no stalk

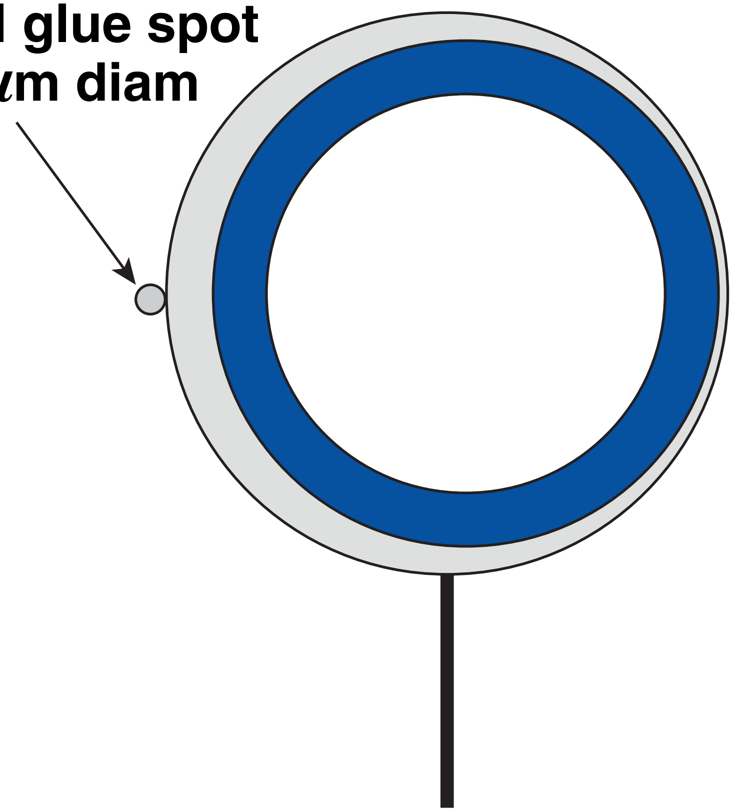
E25735

The influence of low-mode nonuniformities was studied using targets with shell-thickness variations

Not to scale



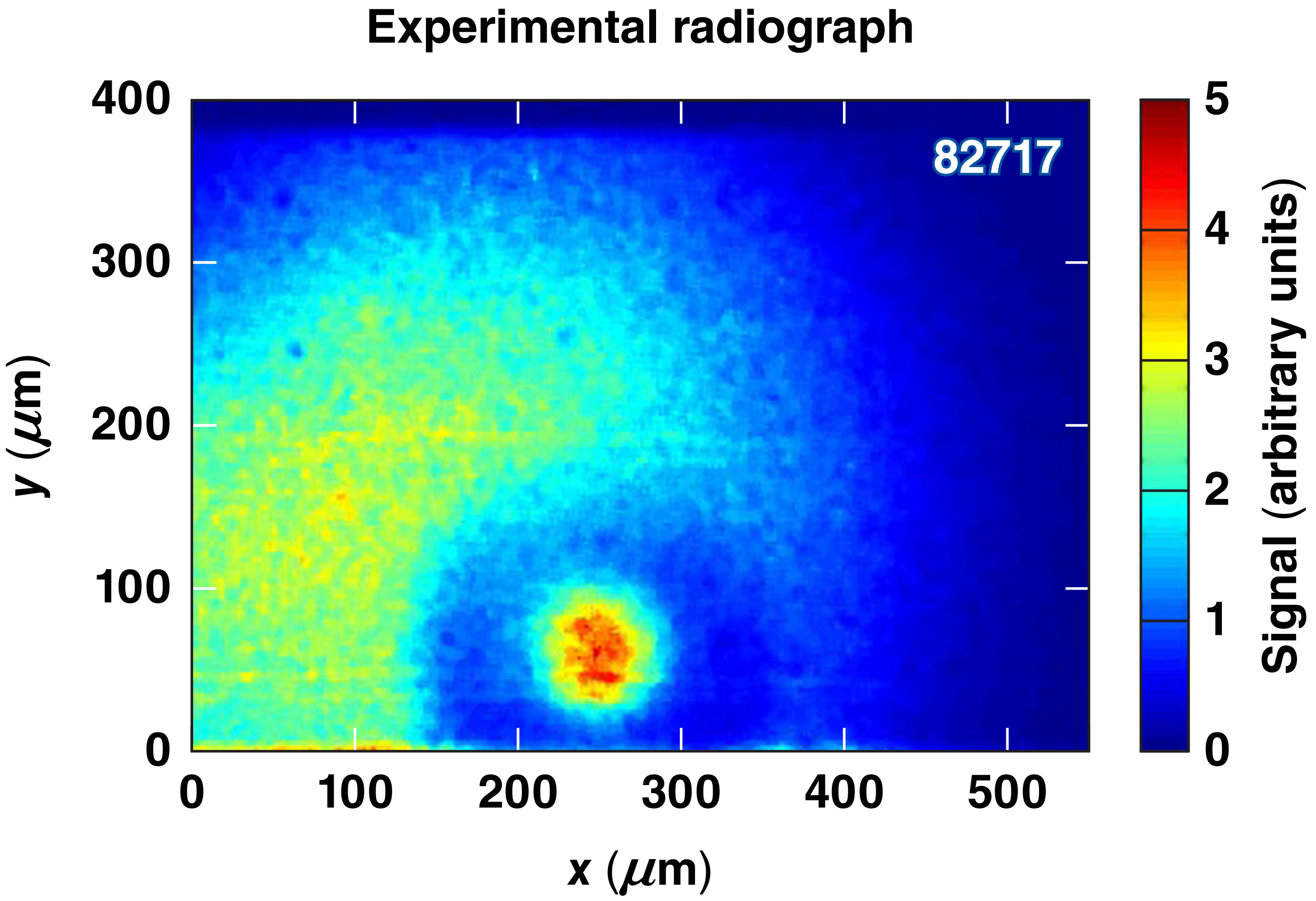
- Shell-thickness nonuniformity ~0.1-μm rms
- Ice-thickness nonuniformity <1-μm rms

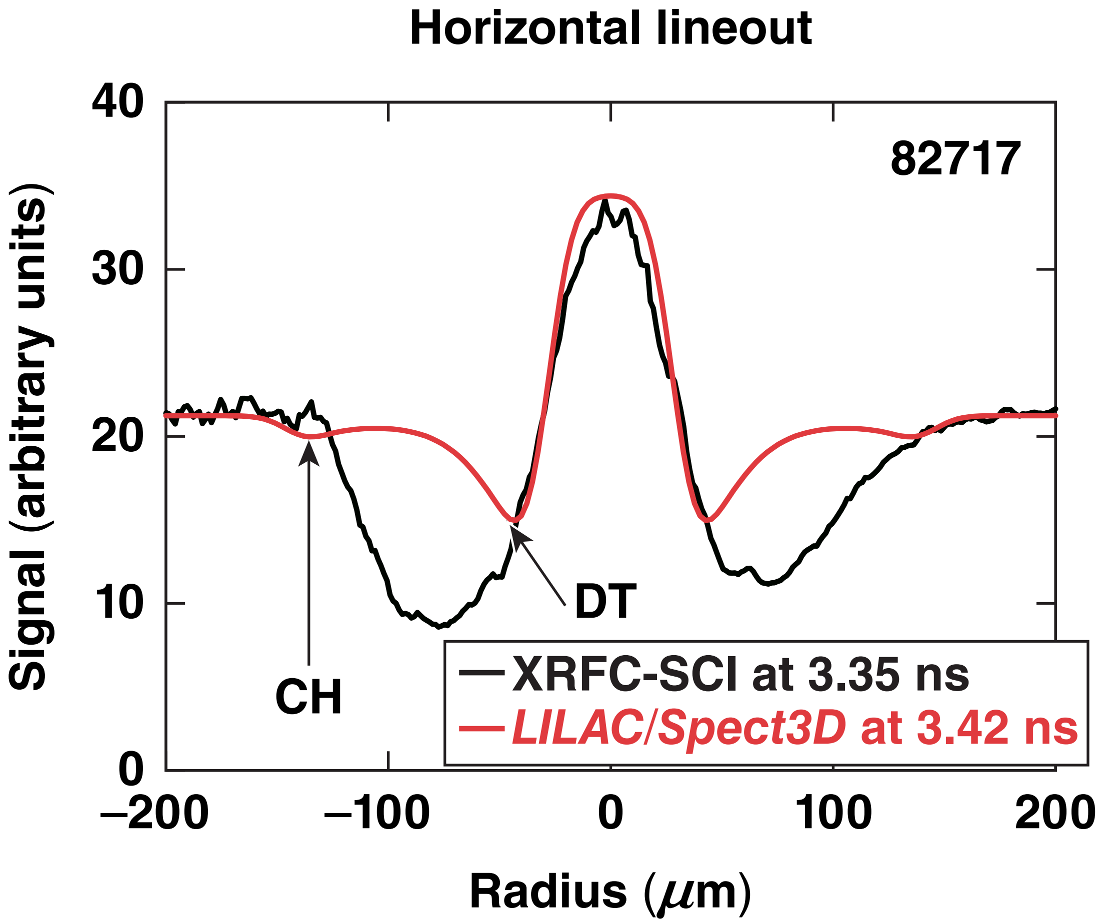


- Shell-thickness nonuniformity 2- to 4-μm peak to peak
- Ice-thickness nonuniformity ~2-μm rms

E25616b

The radiograph from a shell with 4-μm wall thickness variation shows a low-mode structure for a CR ~ 10



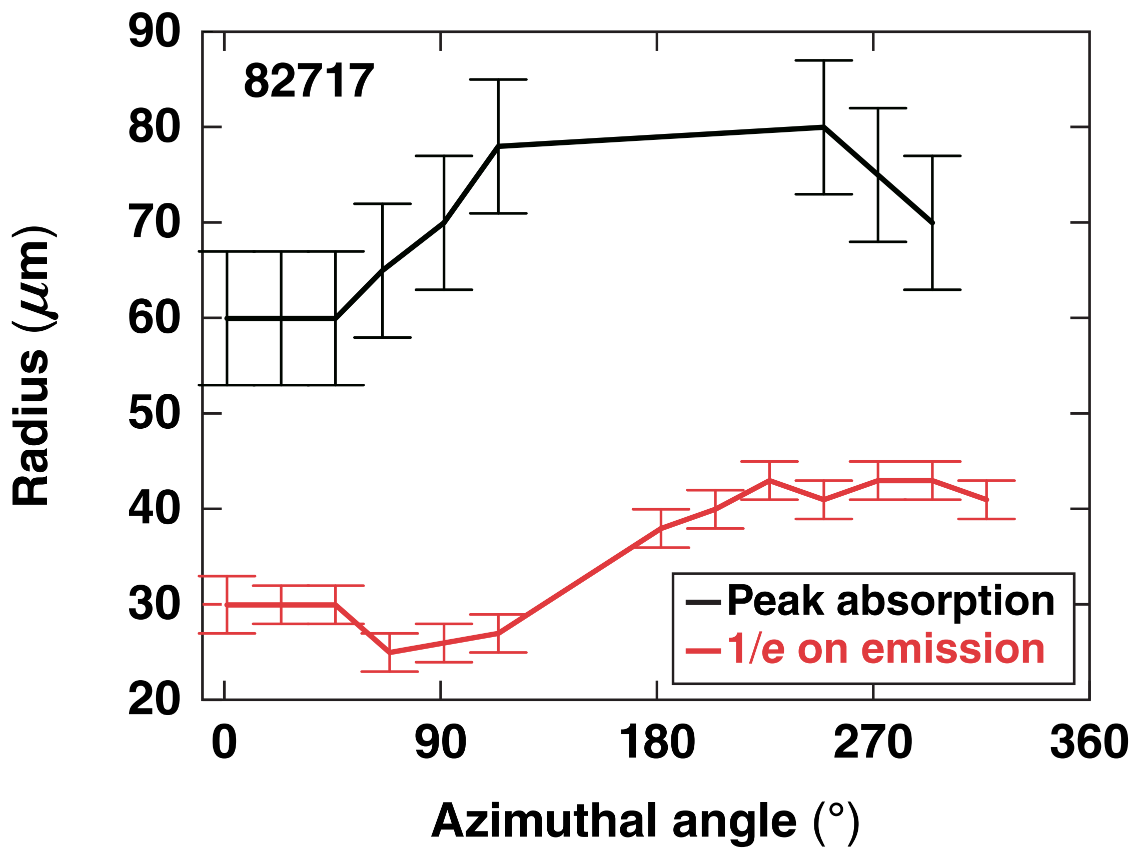


- Exposure time of 40 ps, horizontal 4 μm Δ, ~50 ps before bang
- DT(60 μm) CH(11 μm) 960-μm diam, offset < 10 μm
- α ~ 2, IFAR ~ 15; YOC = 8%, ρR/clean = 41%

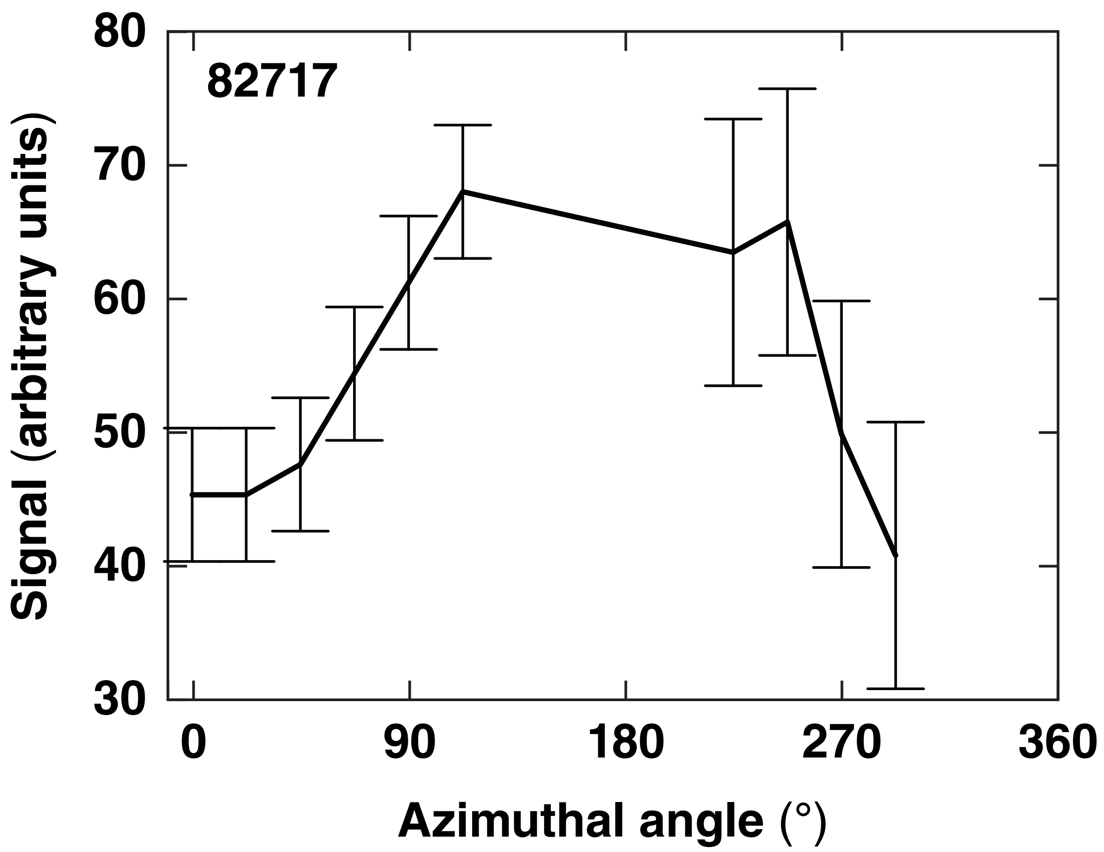
E25621

Both radius and magnitude of peak absorption show a variation as a function of the azimuthal angle

Radius of peak absorption and 1/e of peak emission



Maximum absorption

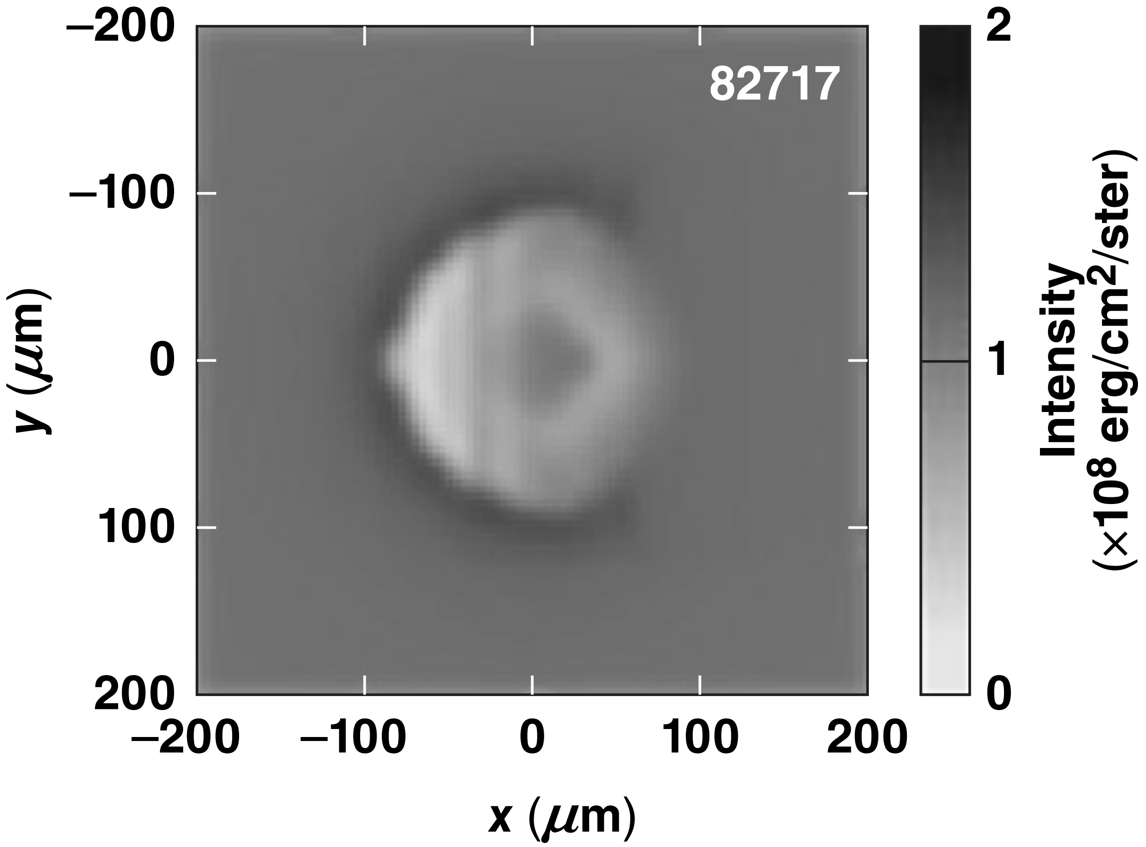


- An $\ell = 1$ of ~5 μm can be introduced by the choice of image center
- $\ell = 1$ with an amplitude of ~10 μm on the peak absorption
- $\ell = 2$ with an amplitude of ~7 μm on the hot spot

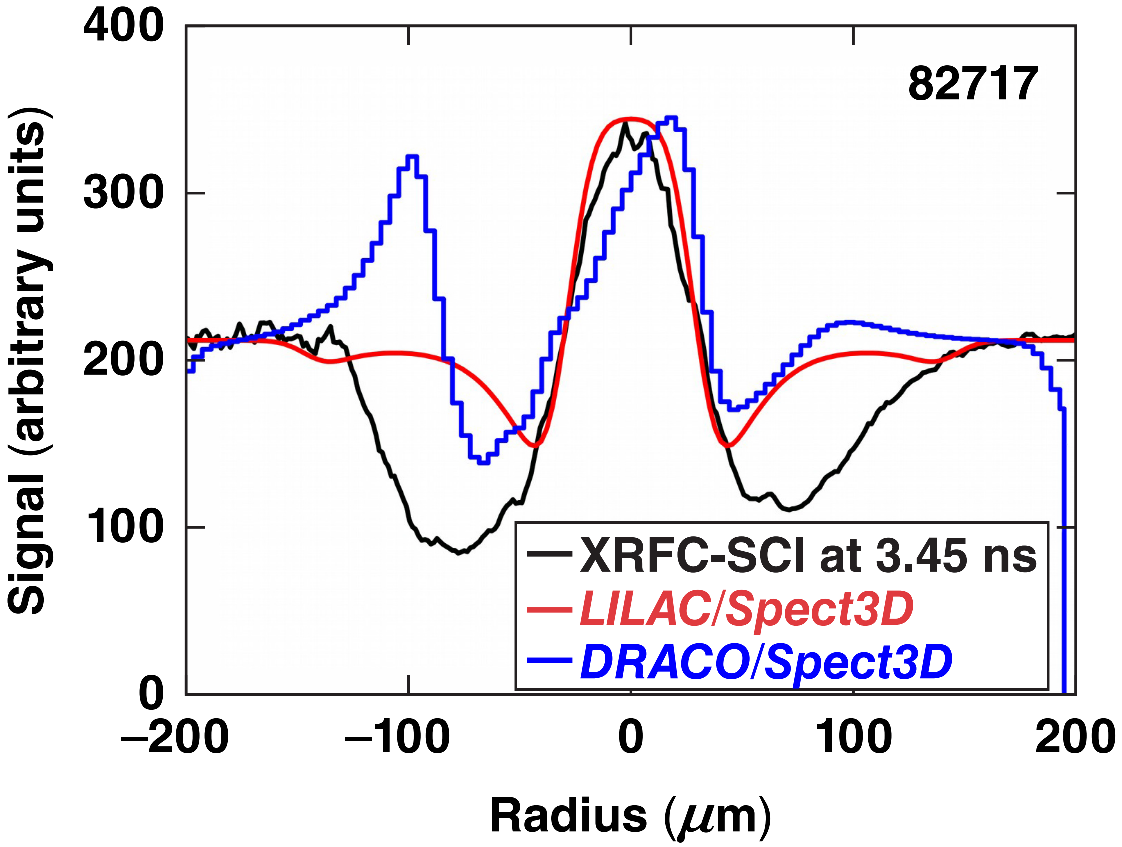
E25622

Post-processed *DRACO** 2-D simulations** show similar features as the experimental data

Simulated radiograph



Horizontal lineout



*P. B. Radha *et al*., Phys. Plasmas 12, 032702 (2005).
**R. Epstein *et al*., TO5.00005, this conference.

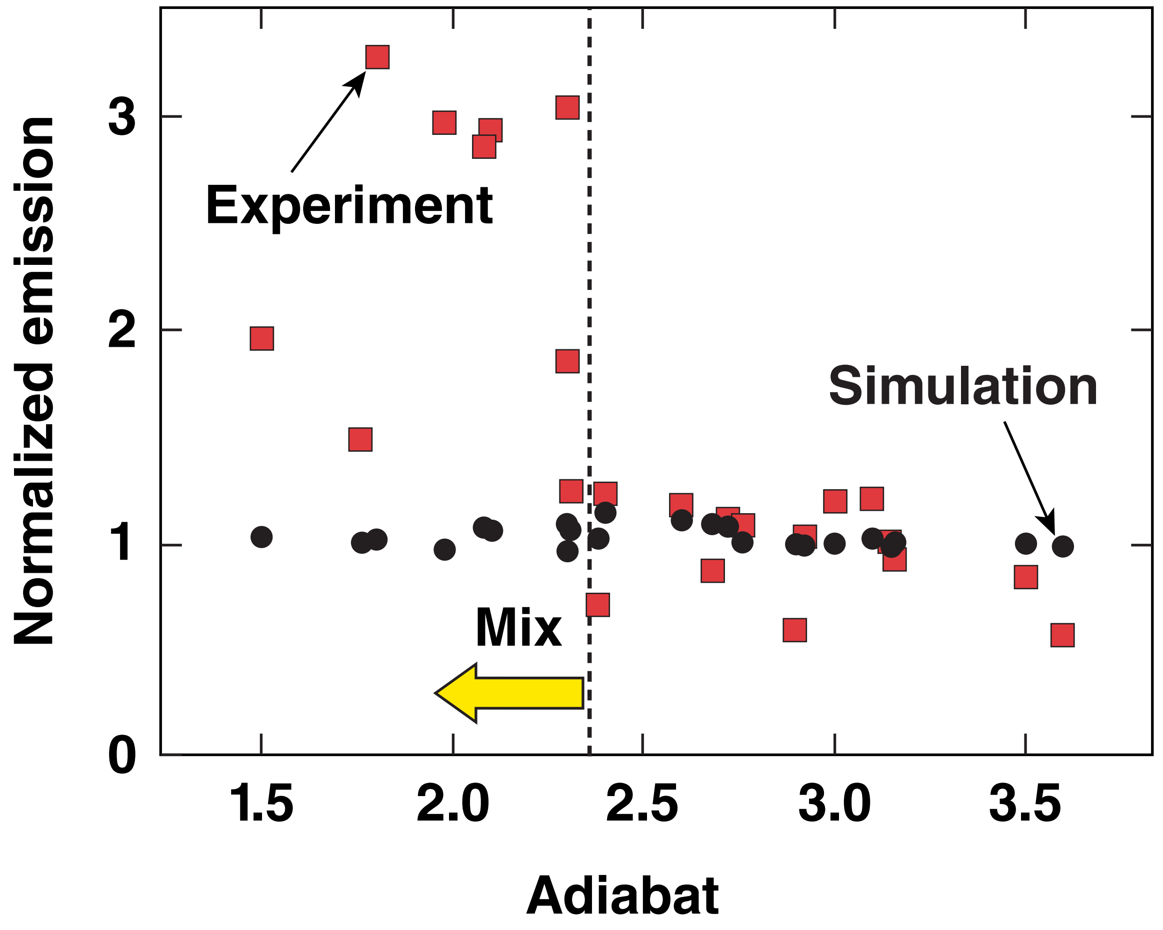
E25671

Outline

- Motivation
- Experimental setup
- Low modes
- **Imprint and mix**
- Localized perturbations

E25670c

Core x-ray emission indicates that carbon from the ablator mixes into the core at peak compression*

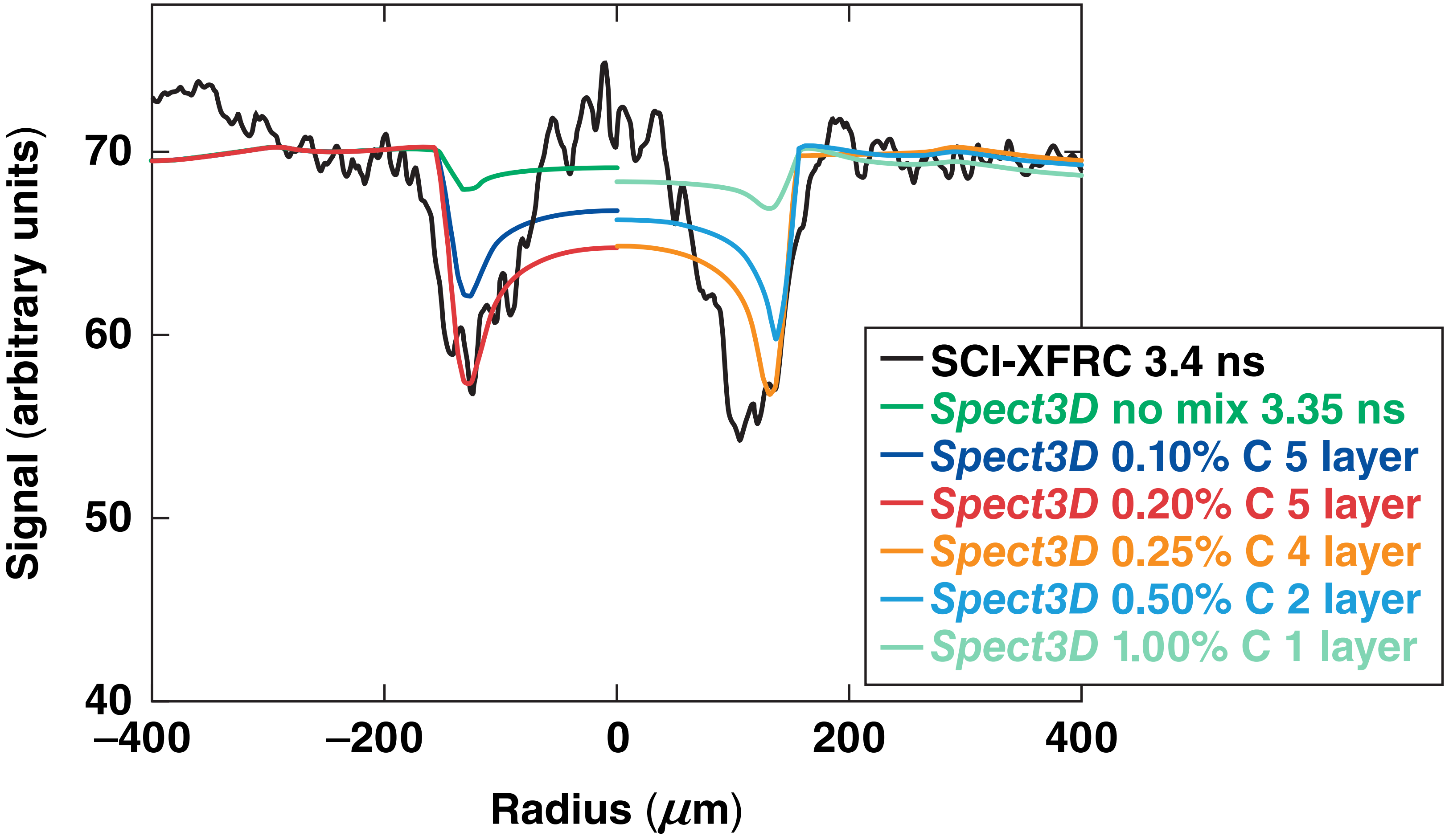


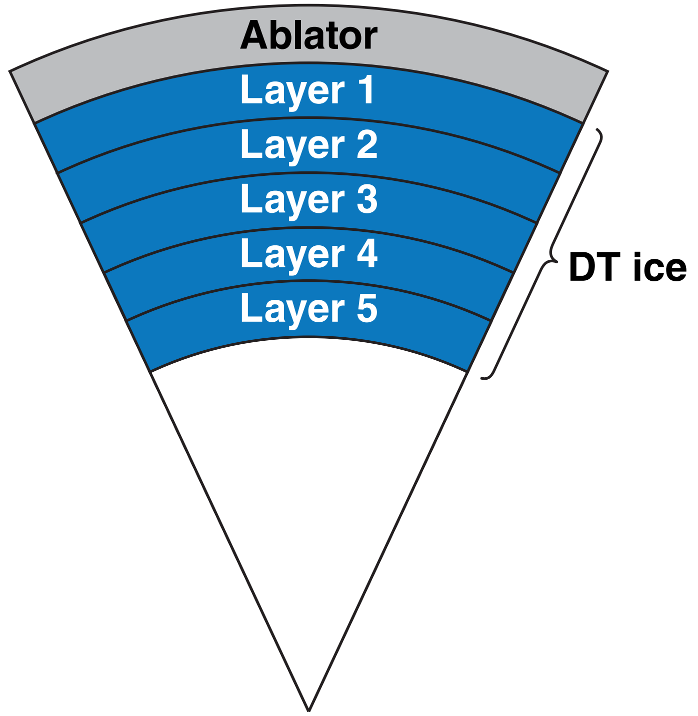
- Radiography was used to study early-time mix with α = 2.5 to 4 and IFAR = 17 to 20 at convergence ratios of 4 to 7
- Some shots had Germanium doped in the shell**

*T. C. Sangster *et al*., Phys. Plasmas 20, 056317 (2013).
**S. P. Regan *et al*., TO5.00004, this conference.

E21741b

Simulations assuming the mixing of carbon into the DT shell can reproduce the measured absorption



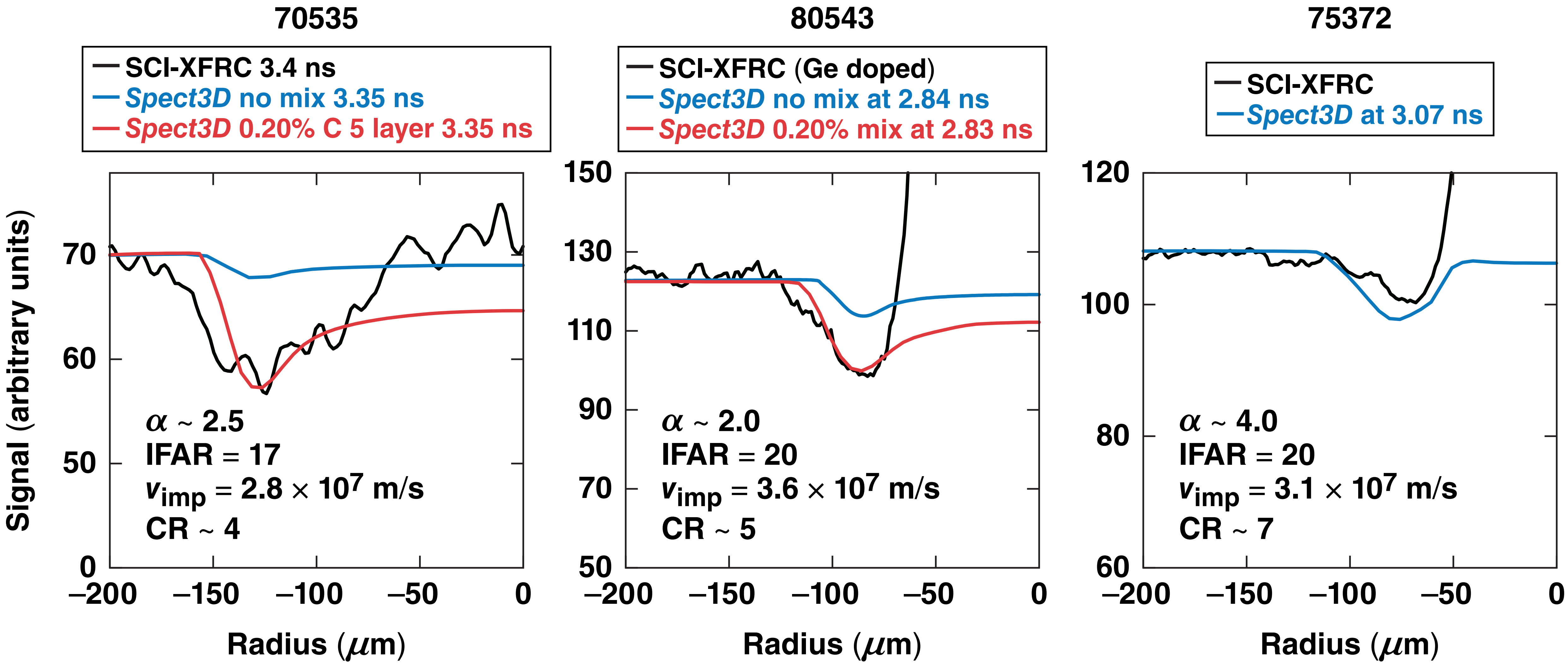


- Exposure time of 200 ps, CR = 4
- DT(60 μm) CH(8 μm), 860-μm diam, offset ~25 μm
- α ~ 2.5, IFAR ~ 17; YOC = 7%, ρR/clean = 78%

The depth of the mixing can be inferred by separating the DT ice into layers in the *LILAC* simulations

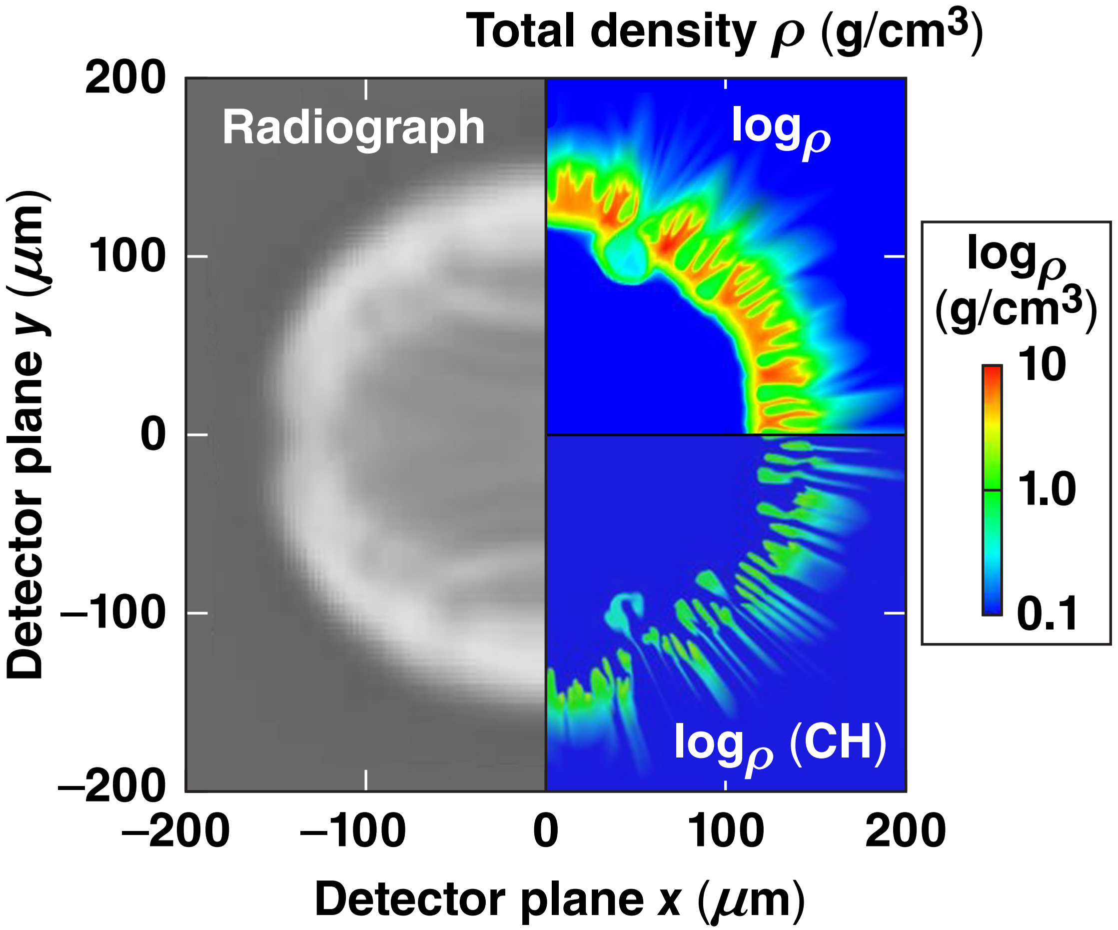
E25628

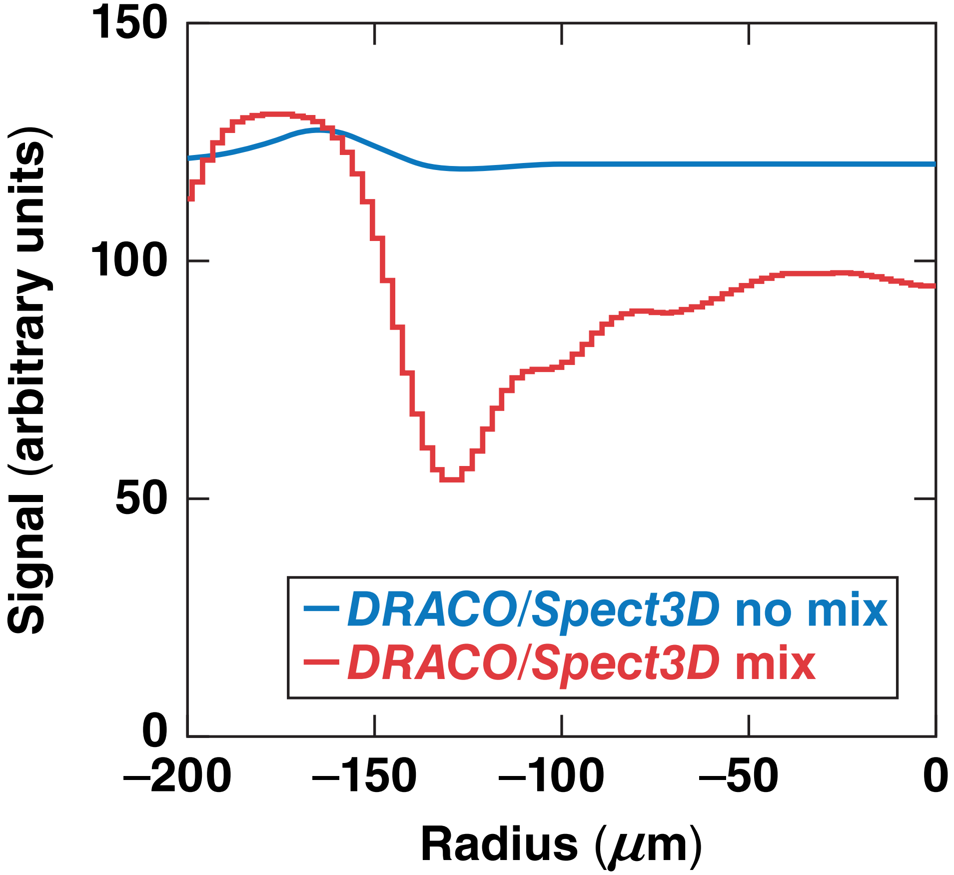
A trend for mixing caused by imprint as a function of adiabat can be inferred from the experimental data



E25631

Post-processed highly resolved *DRACO* simulations show behavior similar to the experiment





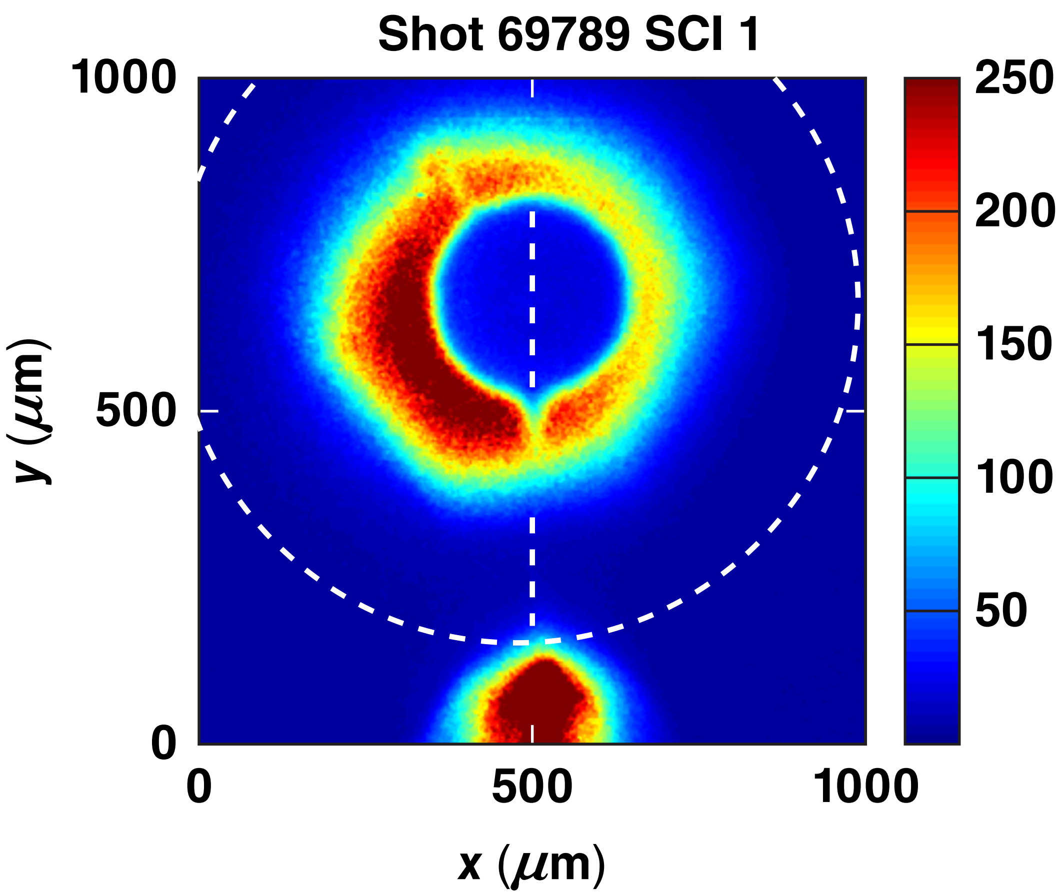
- Simulations include perturbations up to modes of $\ell = 300$
- Low-mode perturbations are included: pointing, timing, energy
- DT(45 μm) CH(11 μm), 860-μm diam
- $\alpha \sim 2.5$, IFAR > 25

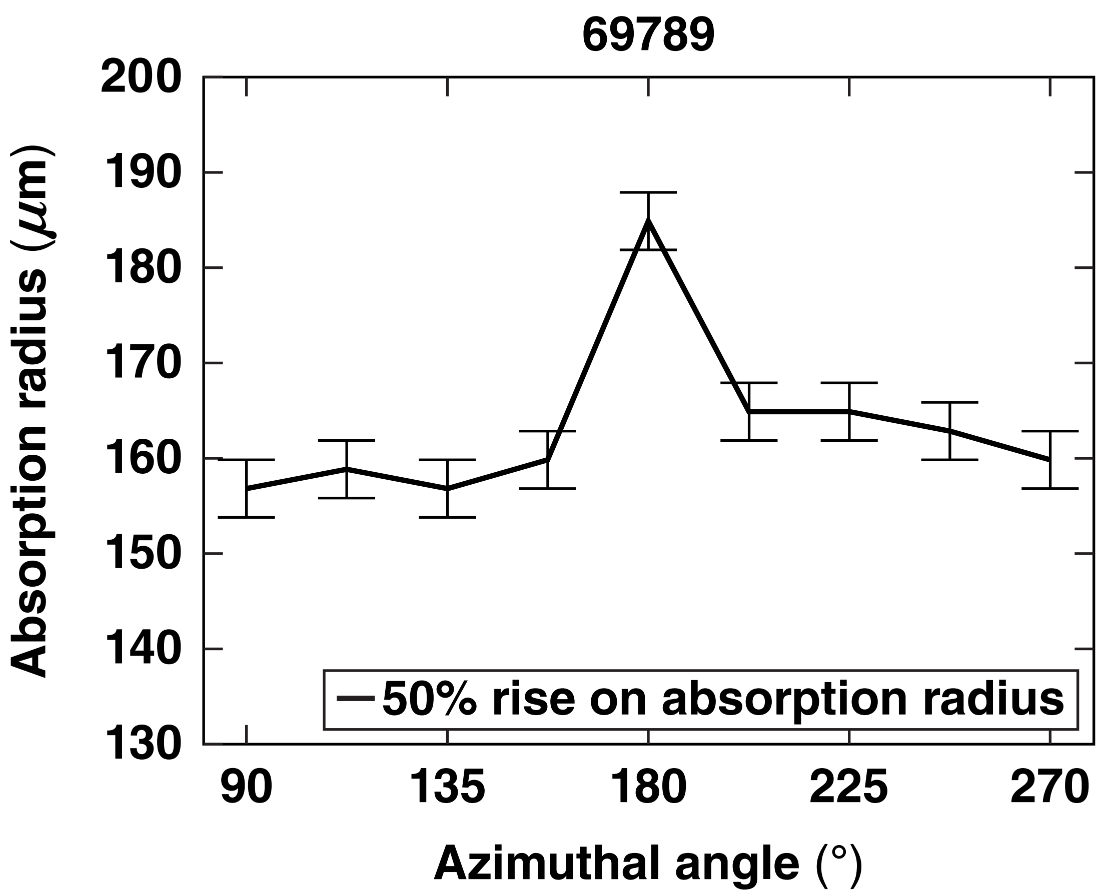
Outline

- Motivation
- Experimental setup
- Low modes
- Imprint and mix
- **Localized perturbations**

E25670d

A 20-μm amplitude stalk feature is seen in backlit images of a mass-equivalent CH target at a CR = 2.5

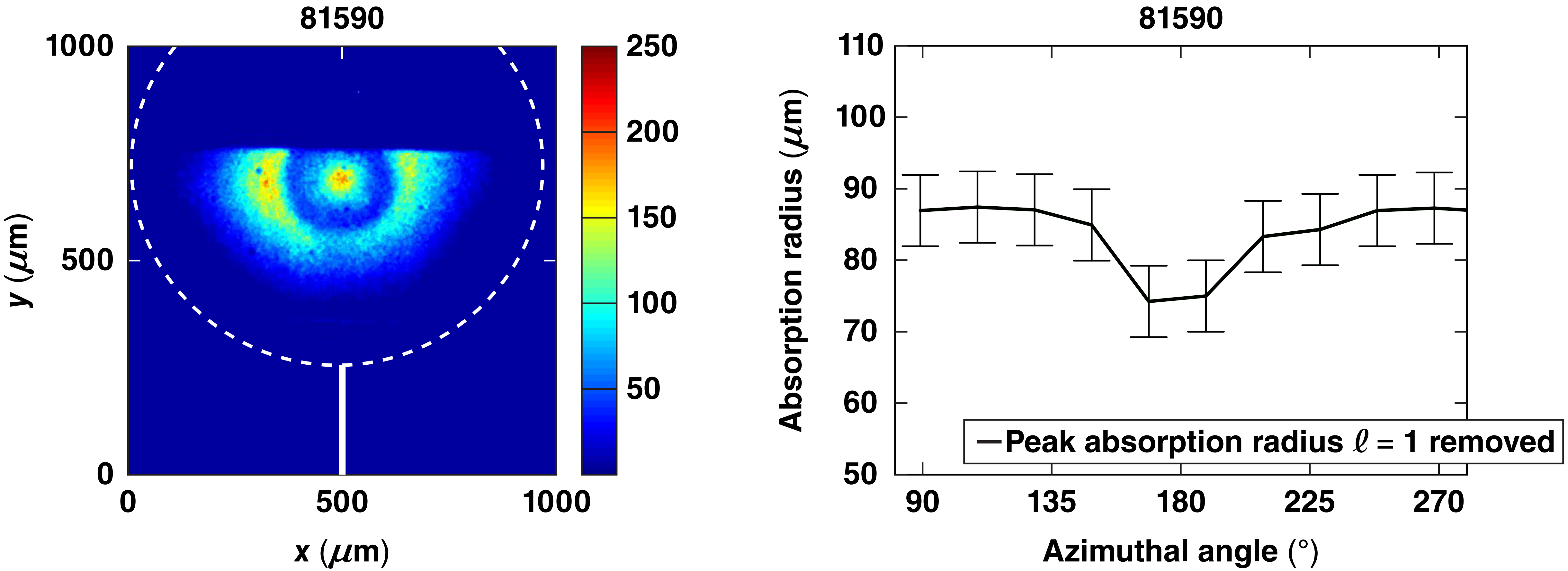




- The radius of the 50% rise on the absorption feature is evaluated by taking lineouts from the center of the image

E22757a

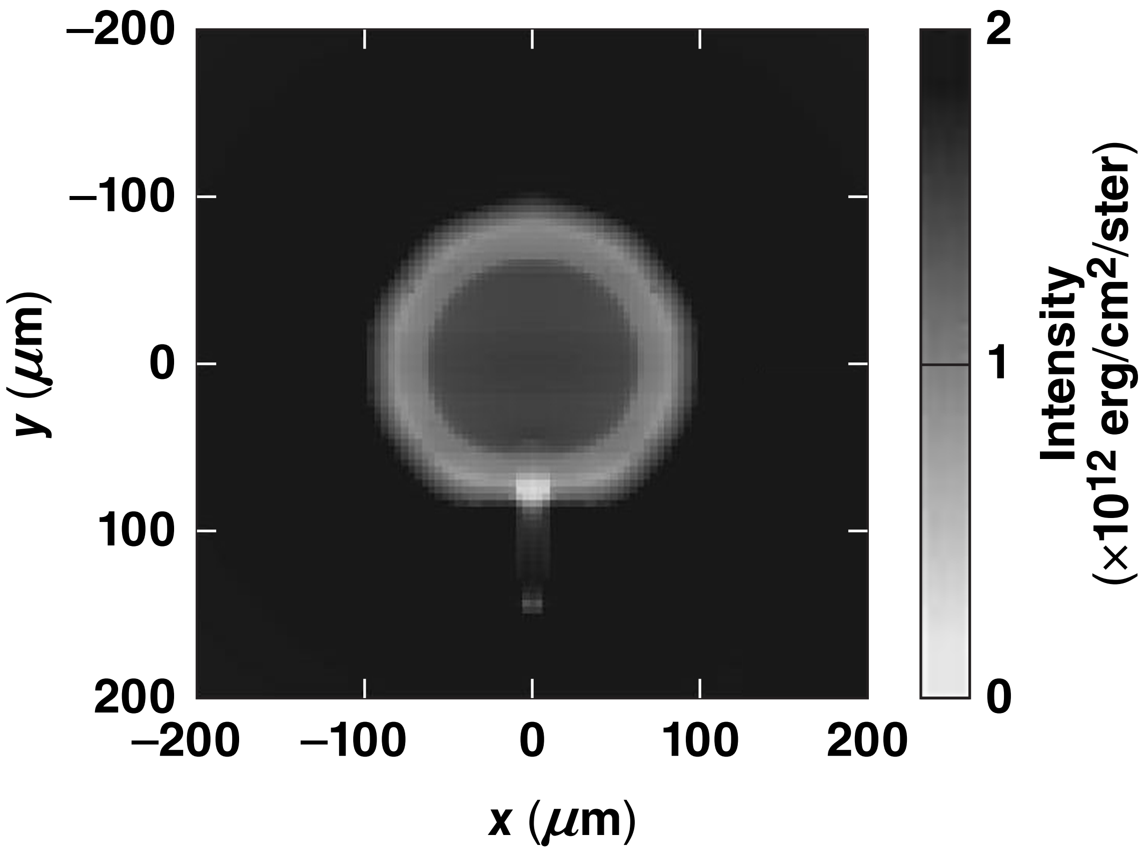
A 10-μm amplitude stalk feature is visible in one low-adiabat (~2.5) cryogenic DT implosion at a CR of 7

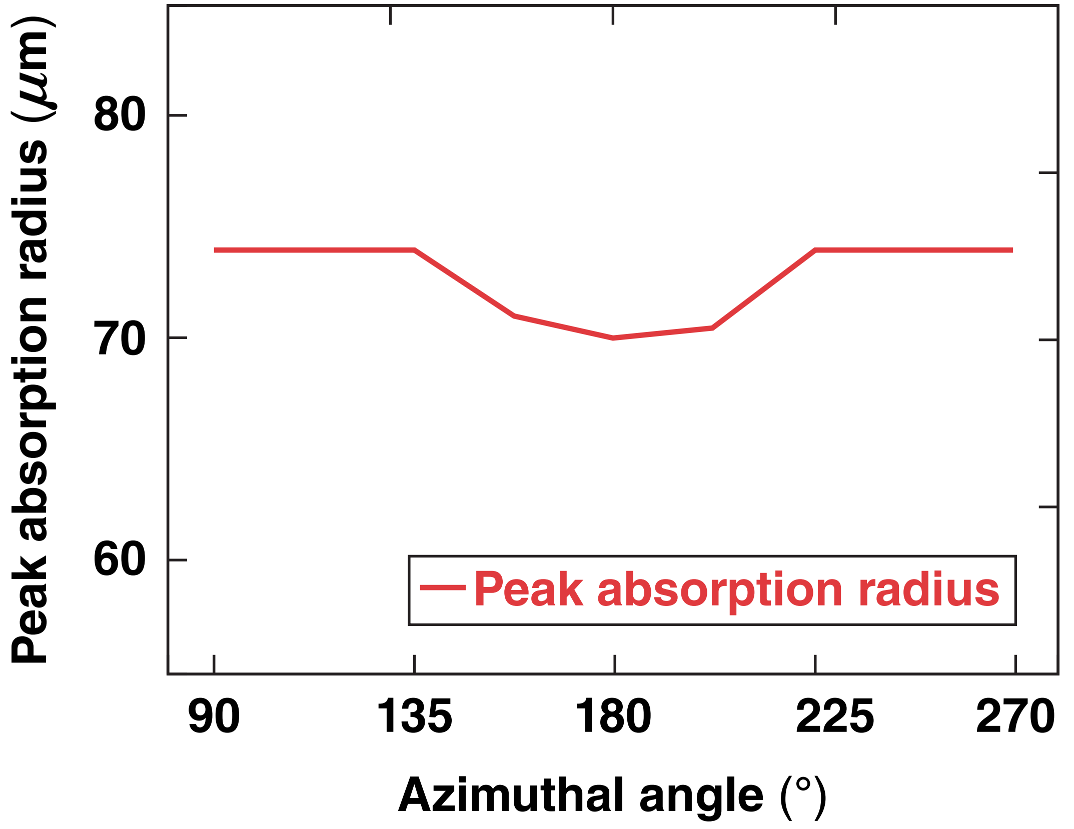


- The radius of peak absorption is evaluated by taking lineouts from the center of the image
- The ℓ = 1 order distortion has been removed

E25624

A comparable stalk effect is also visible in 2-D *DRACO* simulations of a similar target configuration





- *DRACO* simulations are post-processed using *Spect3D*
- The radius of peak absorption is evaluated by taking lineouts from the center of the image

E25672

Quantifying the impact of laser and target imperfections on the implosion performance is an active area of research

- Radiography can be used to study several different effects
  - target placement can be evaluated using pre-imposed target offsets
  - changing the size of the glue spot will help to quantify stalk effects
  - smoothing by spectral dispersion (SSD) on/off experiments will examine laser imprint
- The performance of the shaped crystal imaging system will be improved
  - higher-quality quartz crystals will be used to increase the resolution of the shaped crystal imager; ray tracing shows resolutions $< 1\ \mu m$
  - prepulses and foam targets will be tested to increase the brightness of the Si backlighter

The effects of perturbations on direct-drive DT cryogenic implosions are diagnosed with monochromatic x-ray backlighting

- A crystal imager* is used for short pulse (20 ps), monochromatic x-ray backlighting** (1.865 keV) of 60-beam OMEGA DT cryogenic implosions
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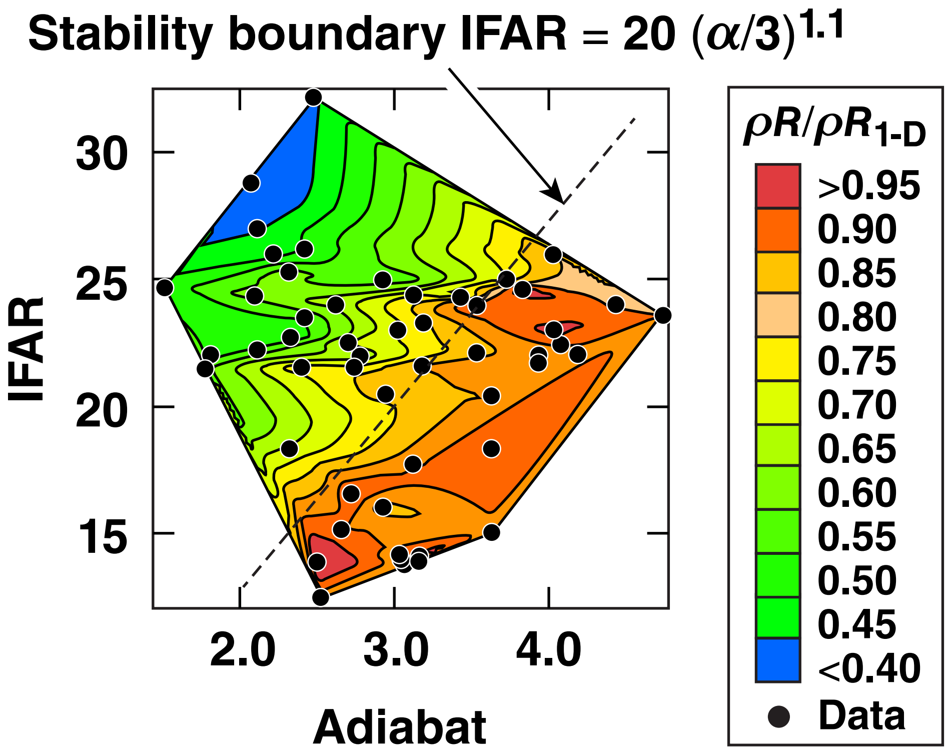
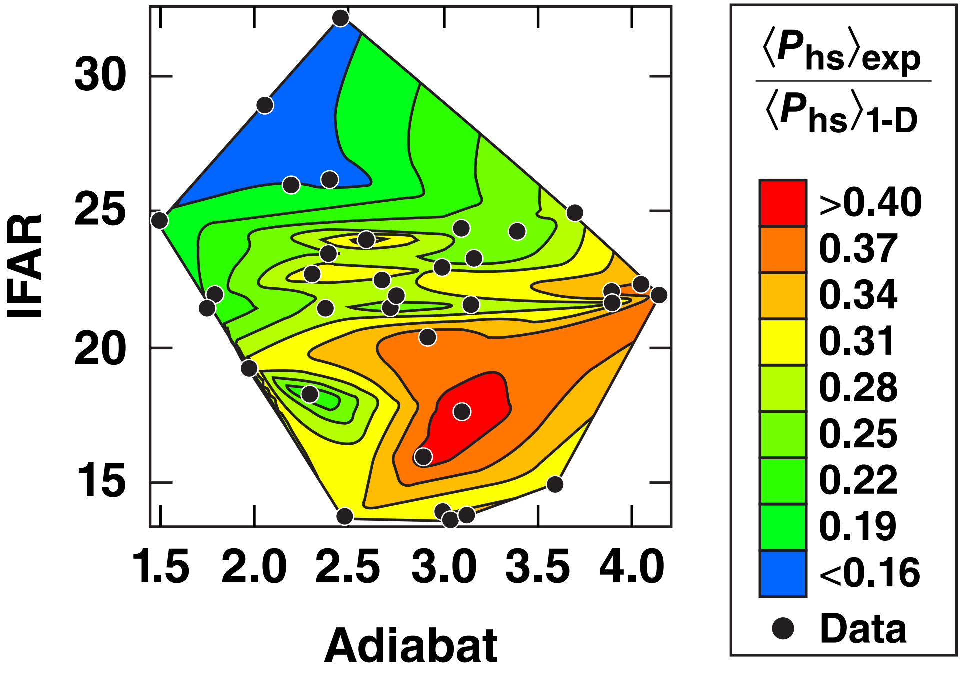
- The level of mixing of plastic ablator with the DT ice has been inferred at in-flight aspect ratios (IFAR's) ~ 20 and adiabats from 2.5 to 4.0

All three sources of perturbations contribute to the performance degradation observed in the experiments.

*C. Stoeckl *et al*., Rev. Sci. Instrum. 85, 11E501 (2014).
**R. Epstein *et al*., TO5.00005, this conference.
†I. V. Igumenshchev, CI3.00002, this conference (invited).

Experimental target performance is a strong function of adiabat and IFAR



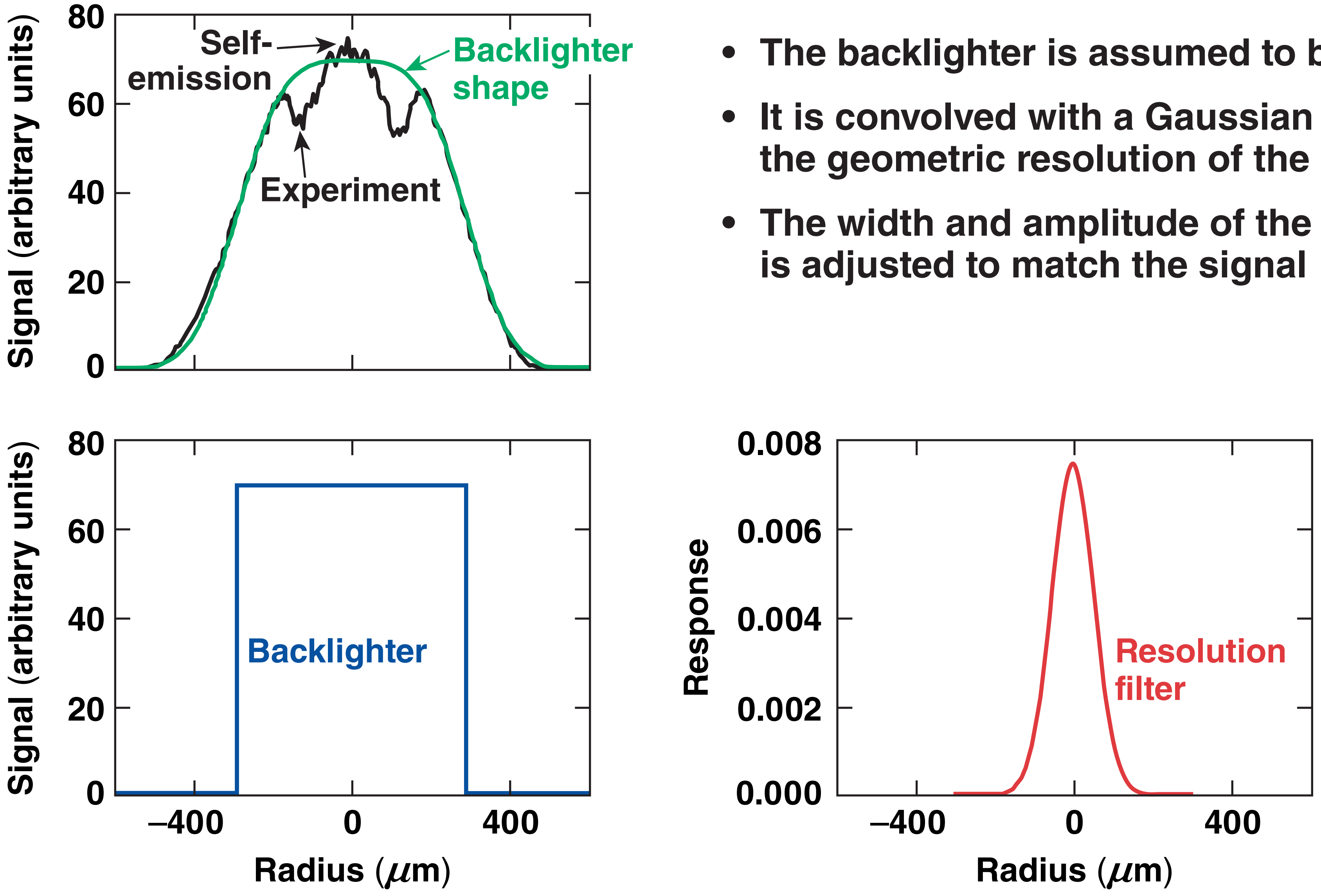


- The ratio of the measured areal density ρR and average hot-spot pressure $\langle P_{hs} \rangle$ over the 1-D simulated values are used as a metric for the performance of the implosion
- The hot-spot pressure can be inferred from the observable quantities: neutron yield, ion temperature, and neutron rate

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

TC12040a

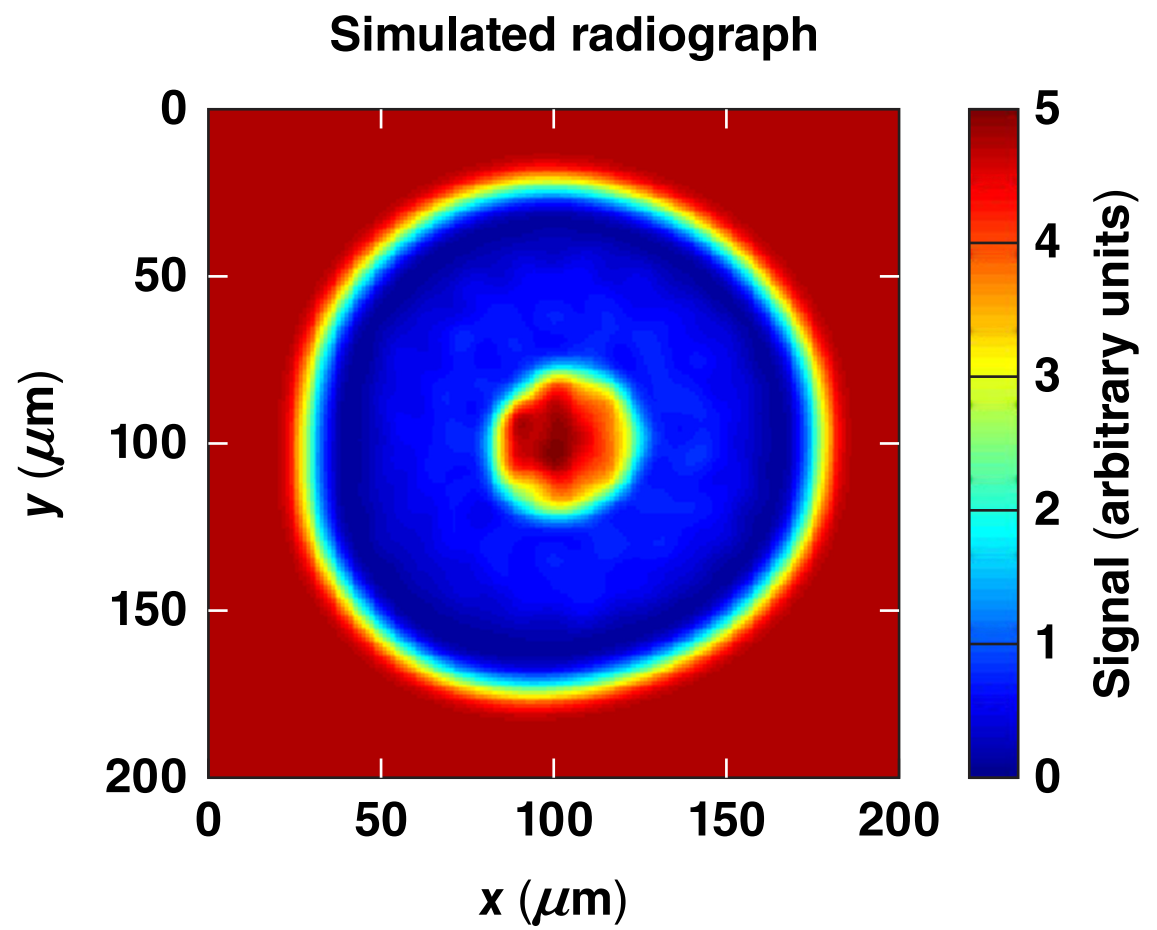
The lineouts of the backlit images from the crystal imager must be corrected for the backlighter shape

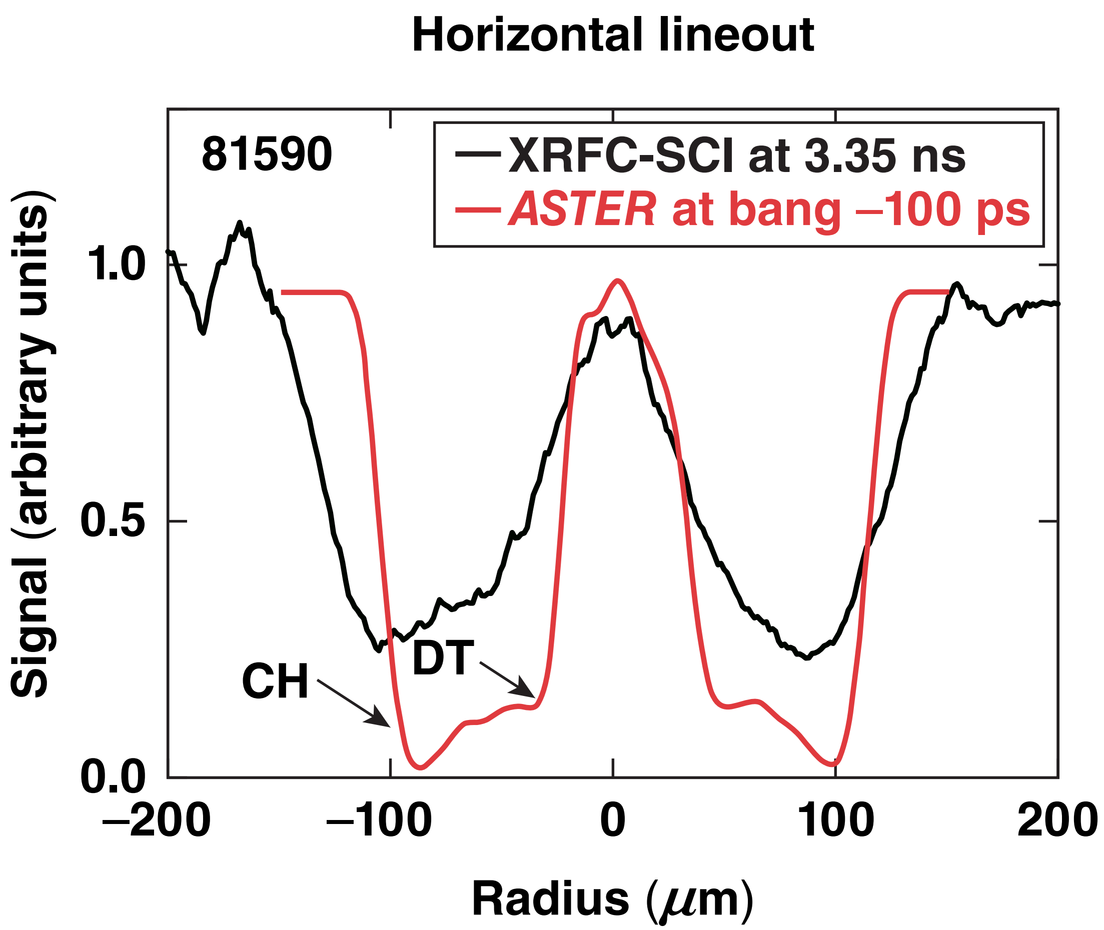


- The backlighter is assumed to be uniform
- It is convolved with a Gaussian representing the geometric resolution of the imager
- The width and amplitude of the backlighter is adjusted to match the signal

E23005b

ASTER 3-D simulations* show similar low-mode features as the experimental data

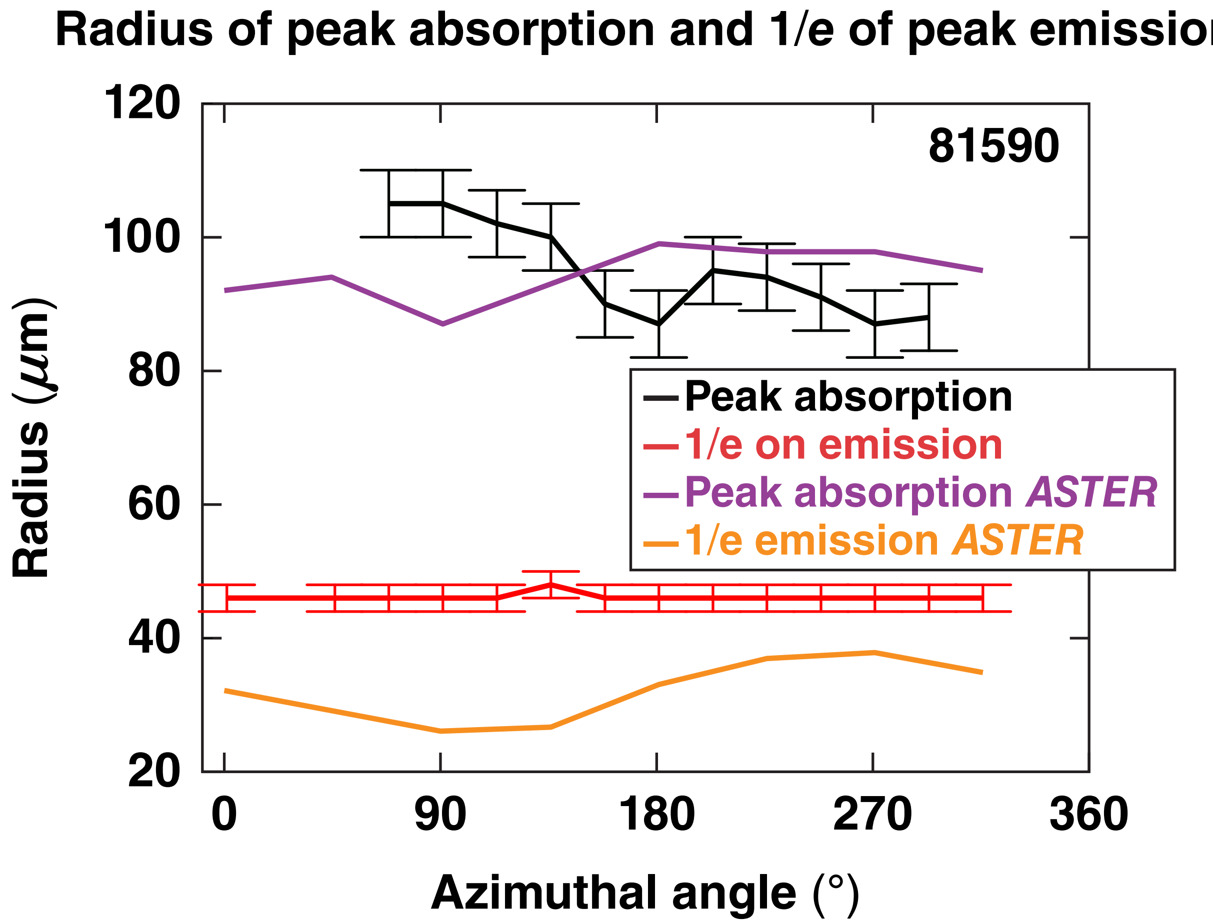


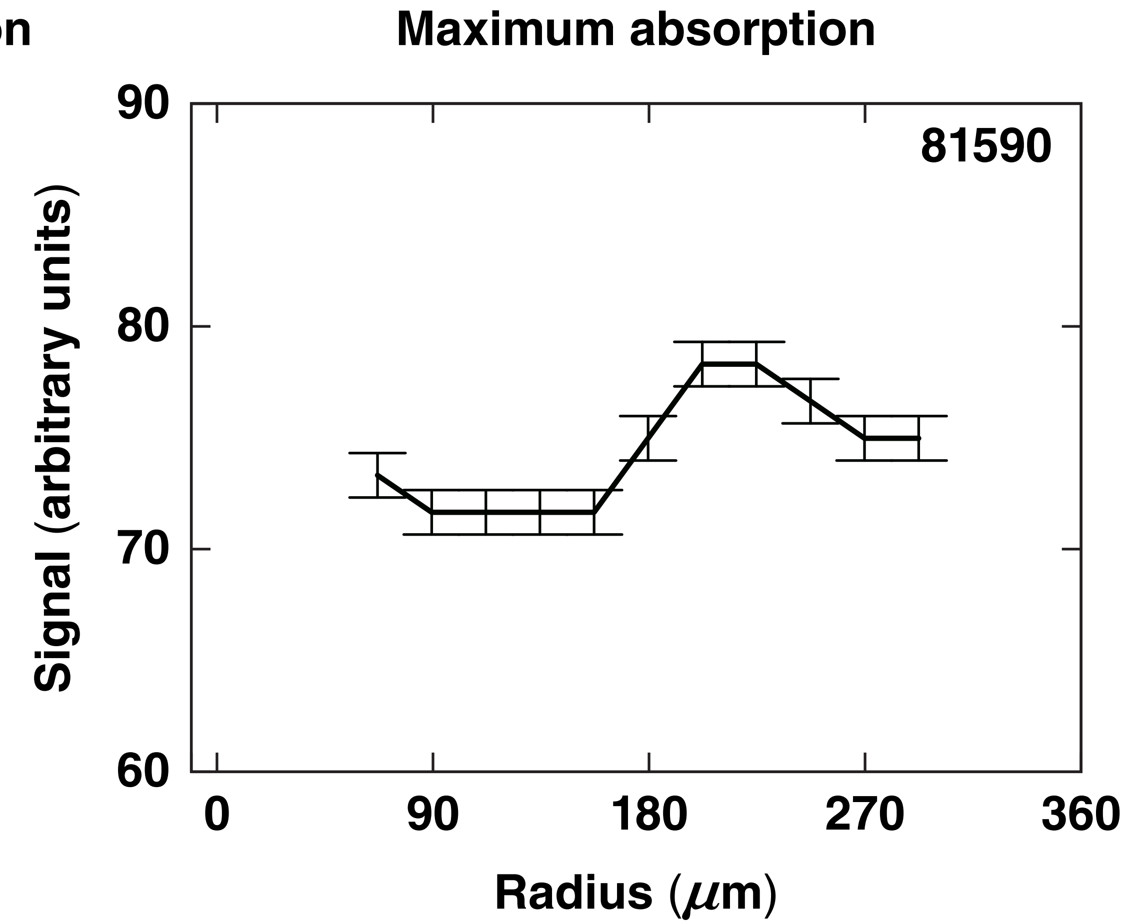


*T. C. Sangster *et al*., Phys. Plasmas 20, 056317 (2013).

E25620

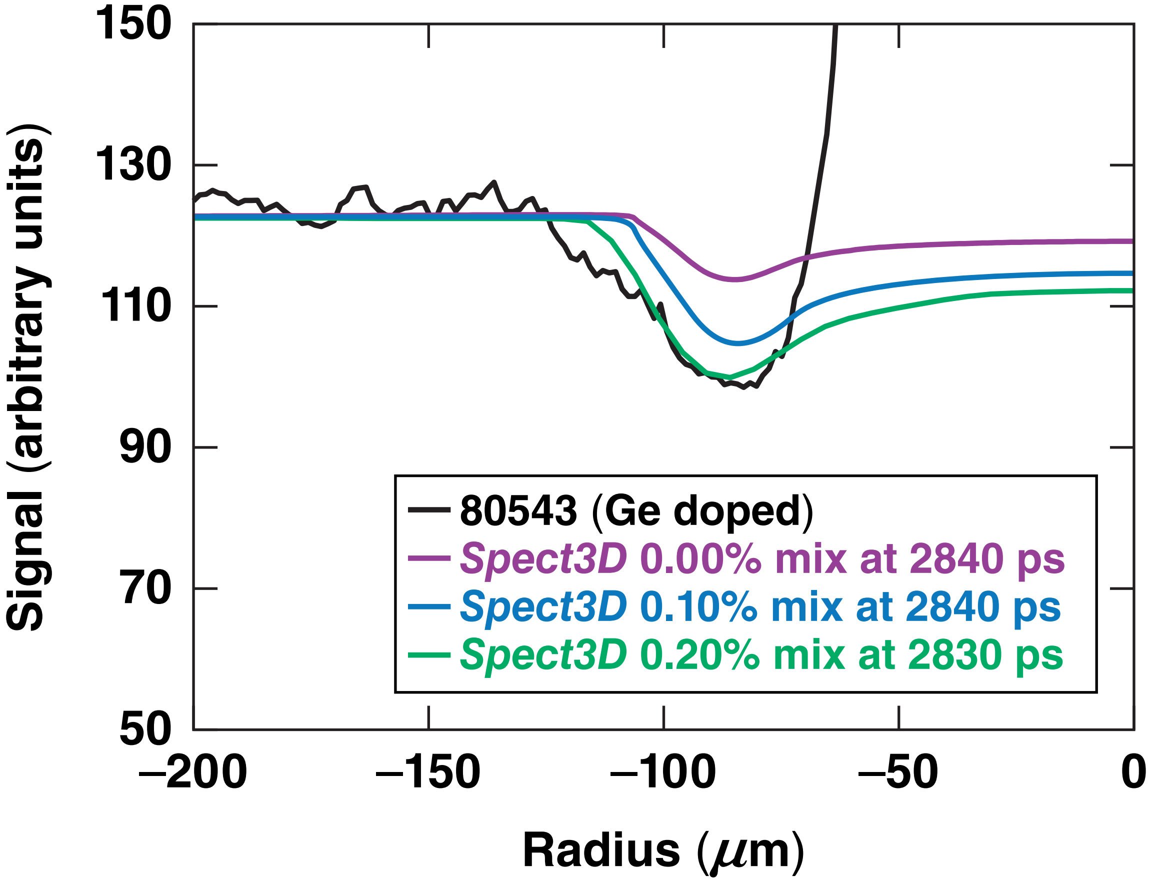
Both radius and magnitude of peak absorption show a small variation as a function of azimuthal angle





- An $\ell = 1$ of ~5 μm can be introduced by the choice of image center
- $\ell = 1$ with an amplitude of ~10 μm on the radius of peak absorption

Spect3D simulations with 0.2% mix of the 0.7% Ge-doped CD shell match the measured absorption

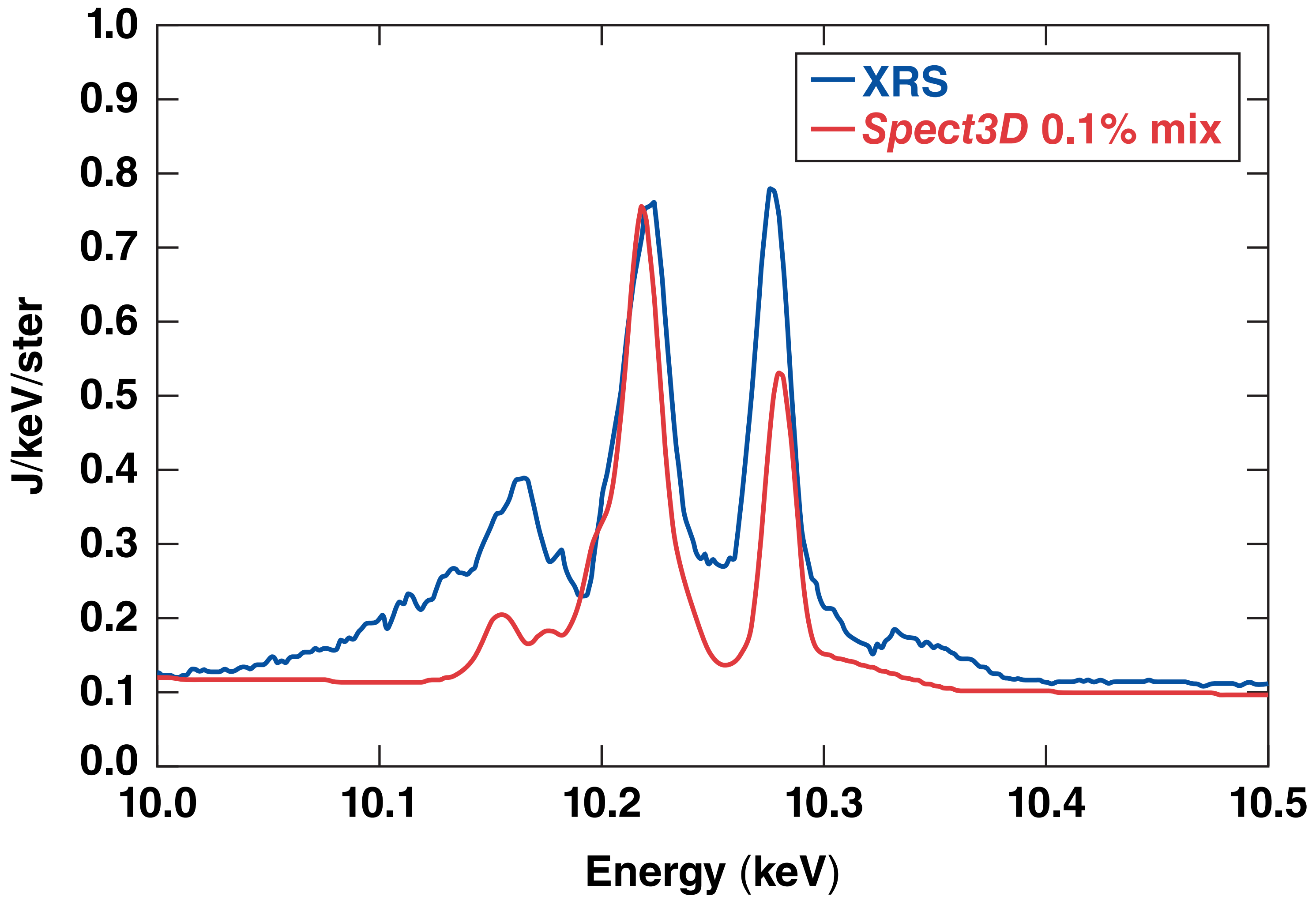


- According to simulations, the mass of the DT shell is ~20 μg
- The mass of the CH(Ge 0.7%) in the shell is ~120 ng
- According to *LILAC*, the hot spot is ~10% of the total mass, therefore assuming only ~50% of the mix gets into the hot spot at ~6 ng

E25629

The emission spectrum from *Spect3D* with 0.1% mix into the core compares favorably with measured spectrum from the x-ray specrometer (XRS)

- XRS is an absolutely calibrated time-integrated x-ray spectrometer
- The emission time is assumed to be 100 ps
- The *Spect3D* spectrum is broadened to account for the instrument resolution
- The experimental spectrum is shifted to match the *Spect3D* continuum



E25630

A number of operational issues prevent the crystal imager from achieving its potential performance

- With an ~15-μm edge response the imager does not achieve its predicted resolution of <5 μm, most likely caused by crystal imperfections
- Pointing variations in the crystal-insertion mechanism lead to clipping on the x-ray framing-camera strip
- Variations in the OMEGA EP beam focus location prevent good centering of the imploded core with respect to the backlighter

E25675

Several improvements to the setup of the crystal-imaging system are in progress

- The cause of this drift in the OMEGA EP beam focus location is being investigated and will be addressed
- A new pointing scheme will be implemented to eliminate the pointing variations in the crystal-insertion mechanism
- A higher-quality quartz substrate will be used in the future to improve the spatial resolution from ~15 μm to $<$5 μm
- An experimental program to increase the brightness of the Si backlighter has started

E25676