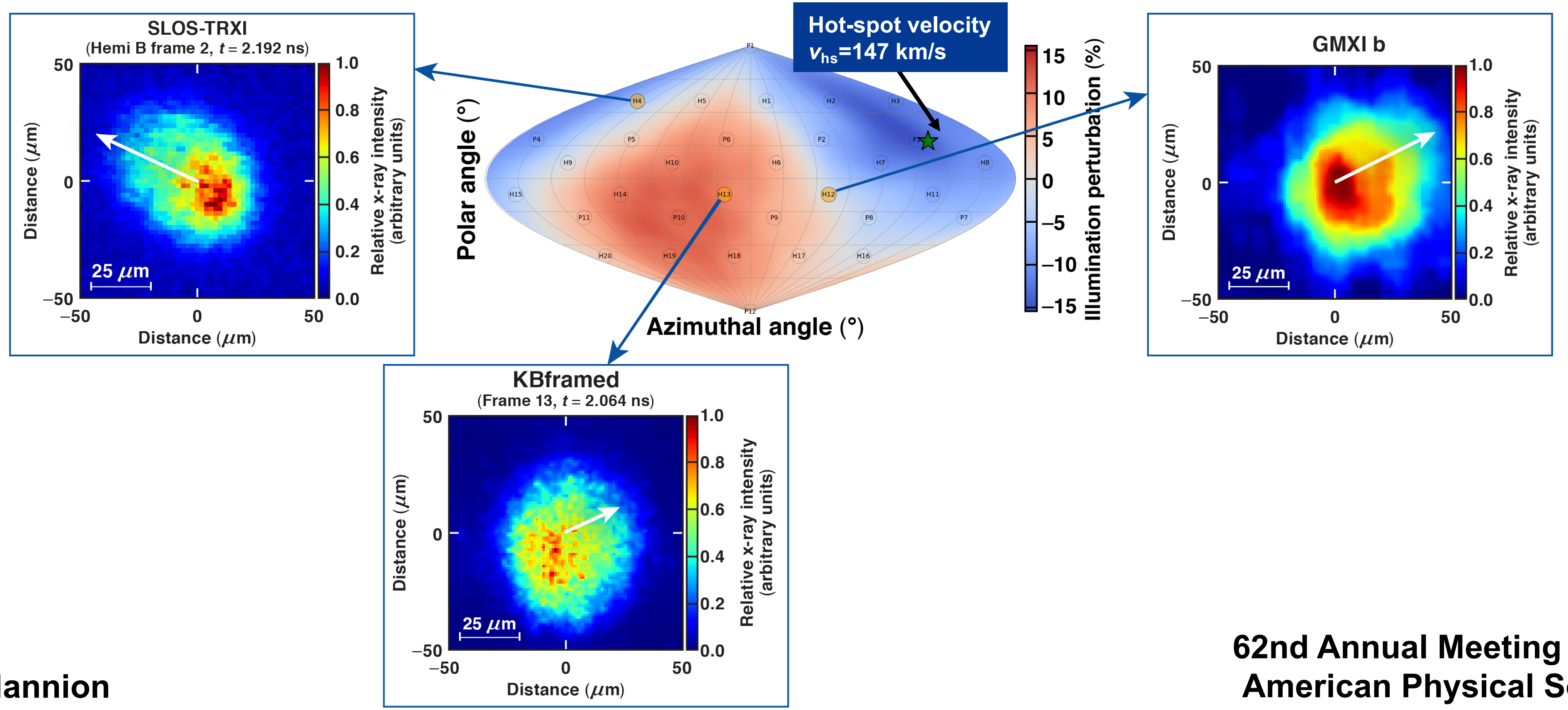
Mode-One Asymmetry in Laser-Direct-Drive Inertial Confinement Fusion Implosions



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University of Rochester
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62nd Annual Meeting of the American Physical Society Division of Plasma Physics
9–13 November 2020

Summary

Causal relationships between $\ell = 1$ asymmetries and implosion performance at stagnation have been observed with 3-D nuclear and x-ray diagnostics on OMEGA

- Mode-1 implosion asymmetries can be varied through initial target positions and laser beam pointing
- Implosions with large seeded mode-1 asymmetries show large hot-spot velocities[*,**] (>100 km/s) and apparent T_i asymmetries along the direction of the mode 1
- The asymmetry observed in hot-spot x-ray images is aligned with the mode-1 direction
- Mode one drive asymmetries are observed to decrease implosion performance
  - hot-spot pressure degradation is strongly related to mode-1 asymmetries
  - accurate post-shot predictions require statistical modeling[†] that account for mode-1 asymmetries

Three-dimensional diagnostic measurements are identifying steps that can be taken to improve symmetry and integrated performance of laser-direct-drive implosions.

* O. M. Mannion *et al.*, Nucl. Instrum. Methods Phys. Res. A 964, 163774 (2020).
**R. Hatarik, Rev. Sci. Instrum. 89, 10I138 (2018).
† A. Lees, TI01.00006, this conference (invited).

Collaborators

K. S. Anderson, R. Betti, E. M. Campbell, D. Cao, C. J. Forrest, V. Yu. Glebov, V. N. Goncharov, V. Gopalaswamy, I. V. Igumenshchev, S. T. Ivancic, D. W. Jacobs-Perkins, J. P. Knauer, A. Lees, F. J. Marshall, Z. L. Mohamed, D. Patel, S. P. Regan, H. G. Rinderknecht, R. C. Shah, C. Stoeckl, W. Theobald, and K. M. Woo

Laboratory for Laser Energetics, University of Rochester

M. Gatu Johnson

Plasma Science and Fusion Center, Massachusetts Institute of Technology

Outline

- Effect of nonuniformities on implosion performance
- 3-D nuclear and x-ray diagnostics on OMEGA
- Mode-1 asymmetries on OMEGA
  - measurements
  - controlling
- Mode-1 asymmetry and target performance

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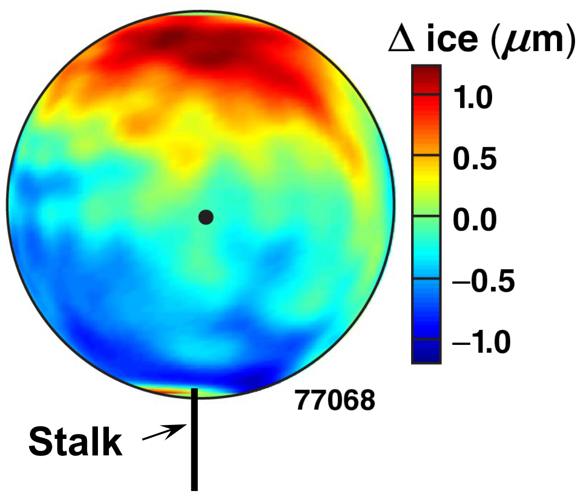
Multidimensional effects are seeded by several sources of nonuniformity in laser direct drive

Target uniformity, engineering features (e.g., target stalk)

Ice-shell thickness variation (cryo)



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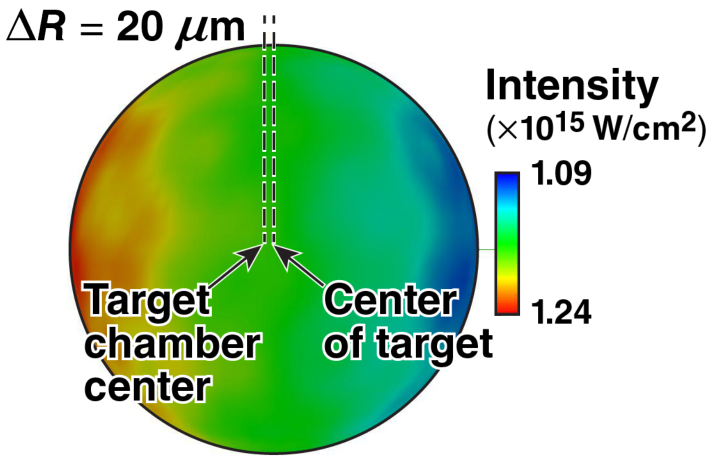
Target positioning



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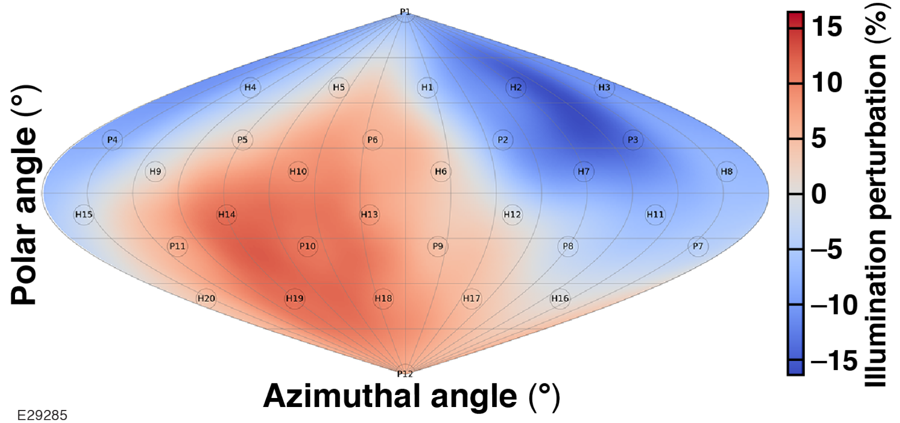
Beam pointing, timing, laser power

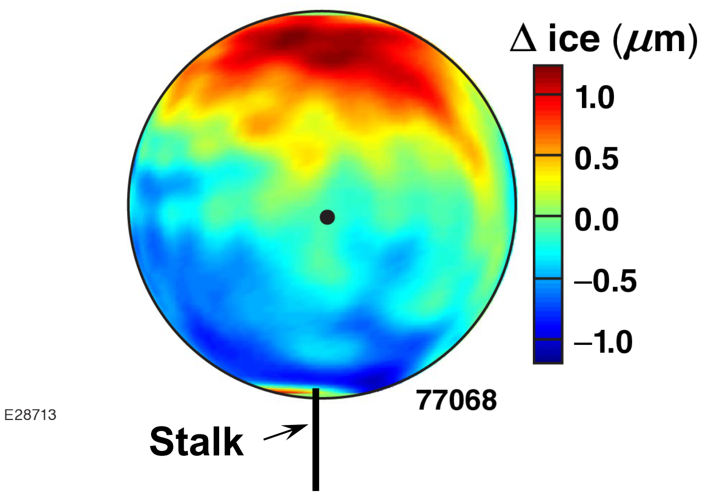


E29285

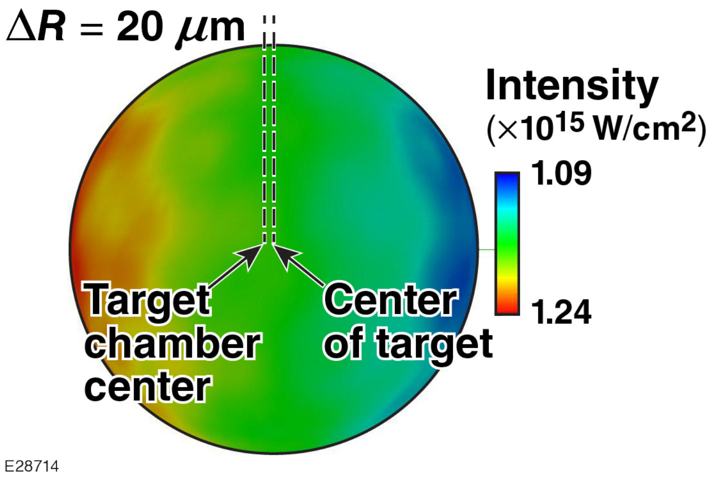
Multidimensional effects are seeded by several sources of nonuniformity in laser direct drive

Target uniformity, engineering features (e.g., target stalk)

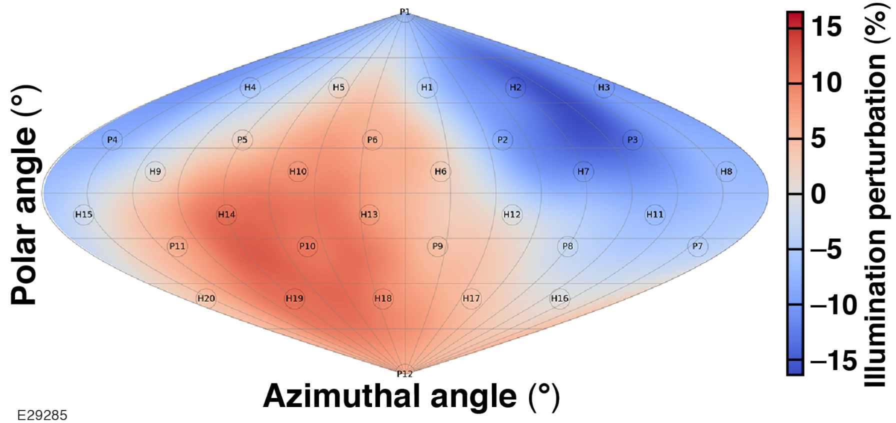
Ice-shell thickness variation (cryo)



Target positioning



Beam pointing, timing, laser power



This talk concentrates on the effects of target offset and beam pointing alignment on the target symmetry at stagnation.

Asymmetric compression of the target leads to an inefficient conversion of shell kinetic energy to hot-spot thermal energy

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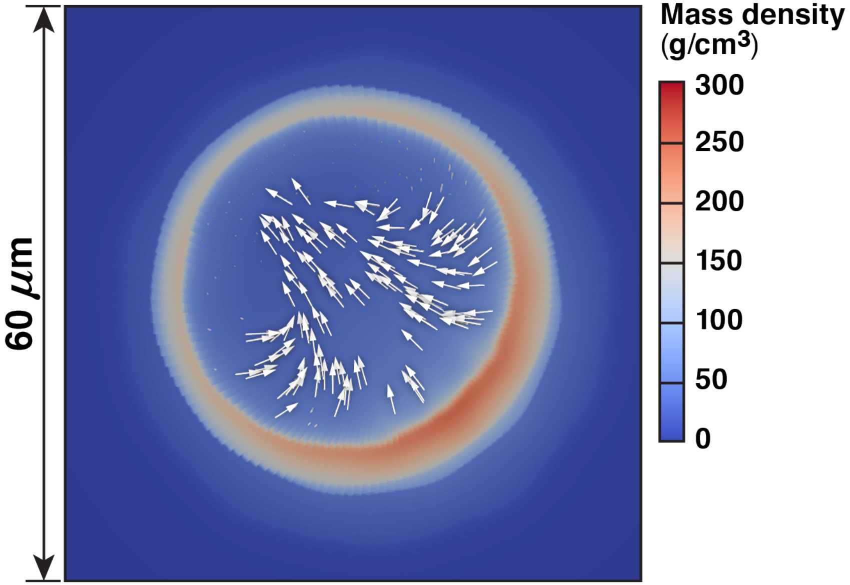
_ASTER_* radiation-hydrodynamic simulation at peak neutron production



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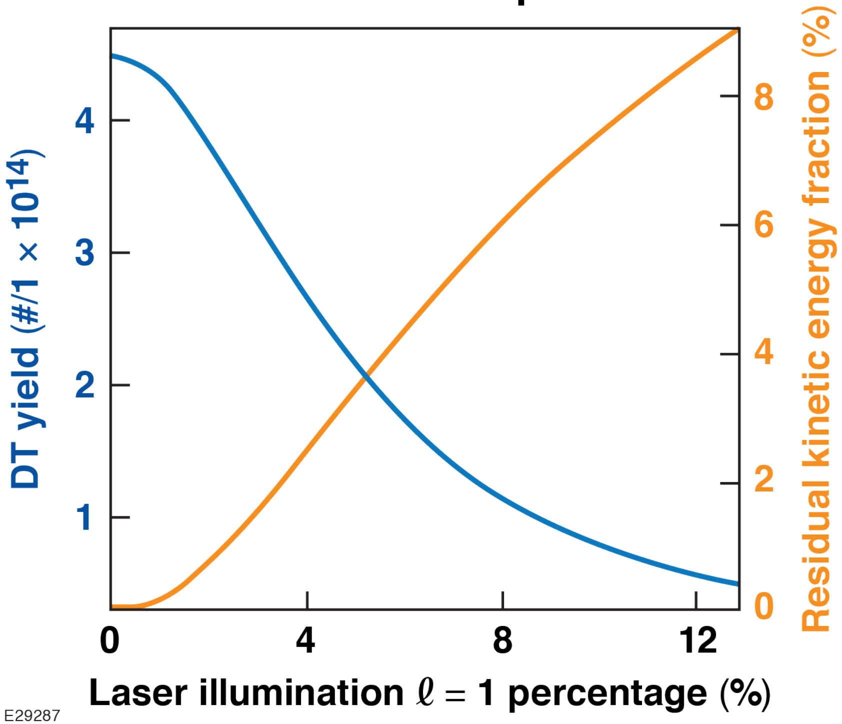
Fusion yield and residual kinetic energy versus mode-1 amplitude,†**



E29287

Three-dimensional simulations indicate the ℓ = 1 asymmetry is the most detrimental to performance.

* I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
** I. V. Igumenshchev *et al.*, BO09.00005, this conference.
† K. M. Woo *et al.*, Phys. Plasmas 25, 052704 (2018).

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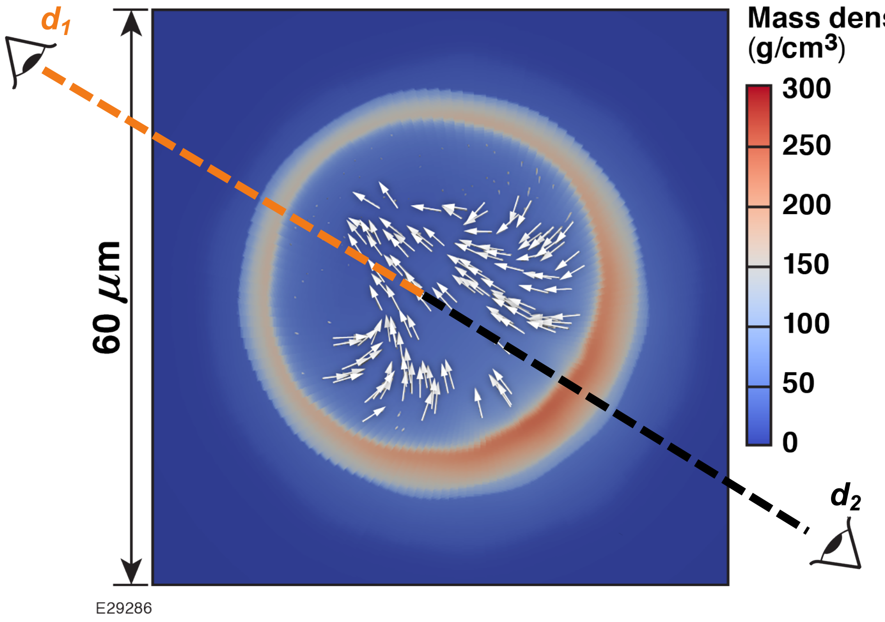
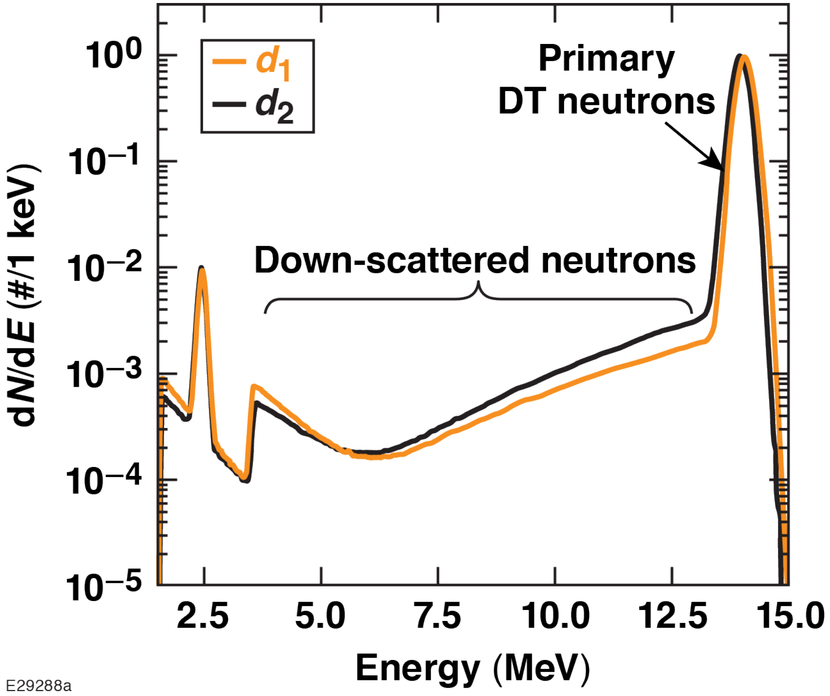


Synthetic neutron diagnostics

Synthetic neutron energy spectrum emitted from target**



* I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
** F. Weilacher, P.B. Radha, and C. Forrest, Phys. Plasmas 25, 042704 (2018).

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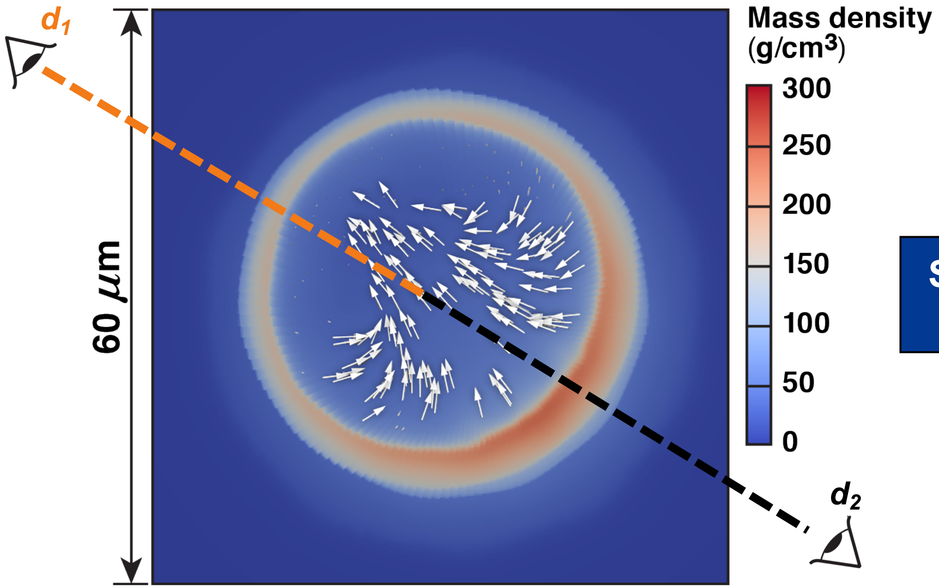

E29286

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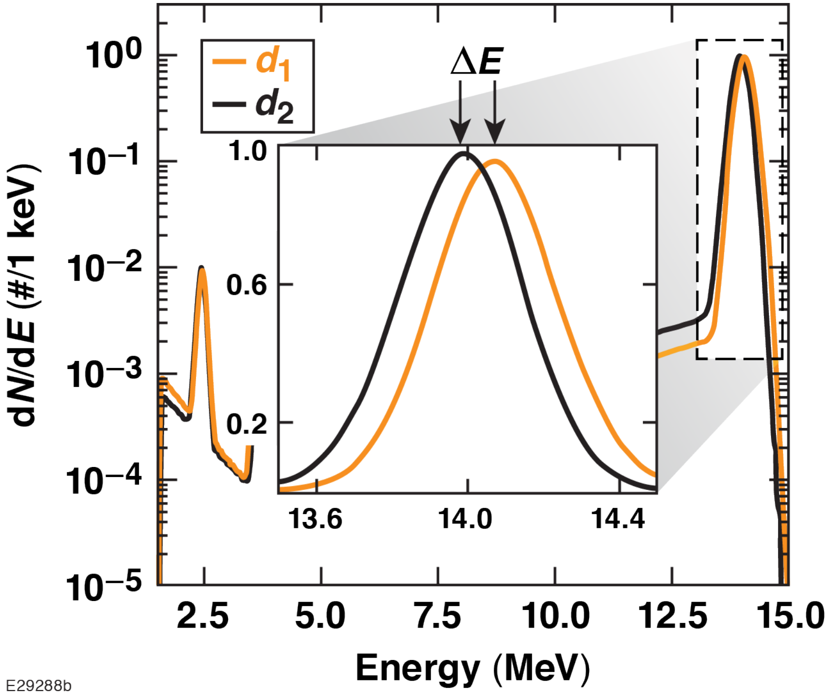

E29288b

Three-dimensional neutron diagnostics provide information on the hot-spot velocity (first moment), apparent ion temperature (second moment), and the shell areal density (down-scatter ratio).

* I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
** F. Weilacher, P.B. Radha, and C. Forrest, Phys. Plasmas 25, 042704 (2018).

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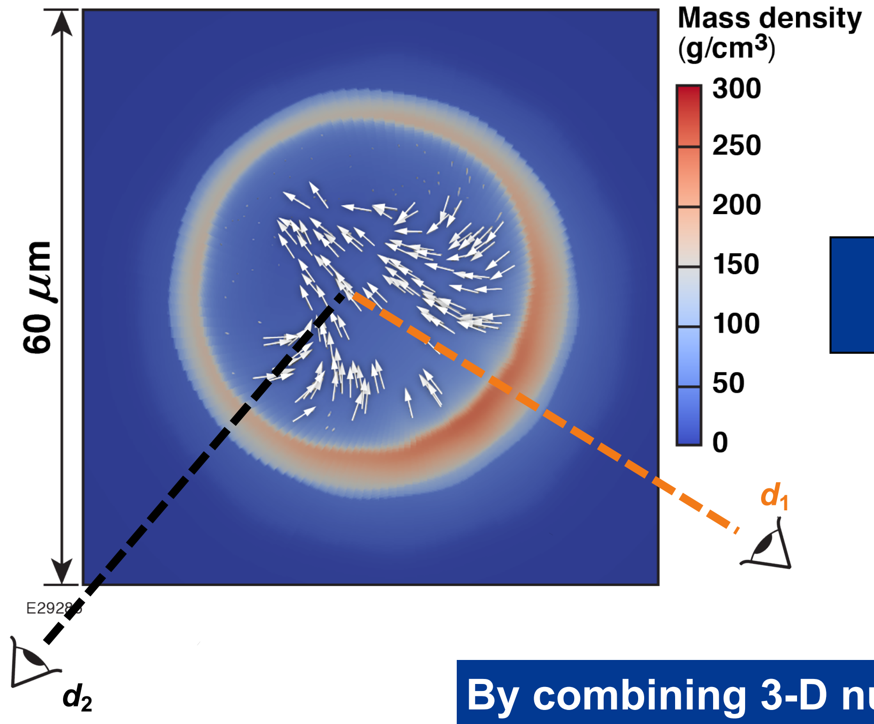
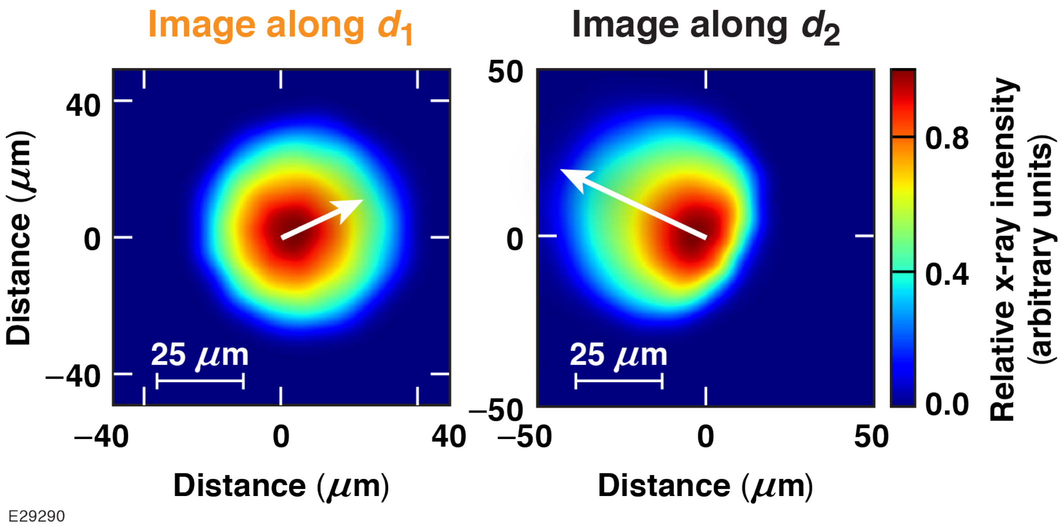


Synthetic x-ray diagnostics

Synthetic hot-spot x-ray images at stagnation



By combining 3-D nuclear and x-ray measurements, the direction and magnitude of mode one asymmetry can be identified.

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

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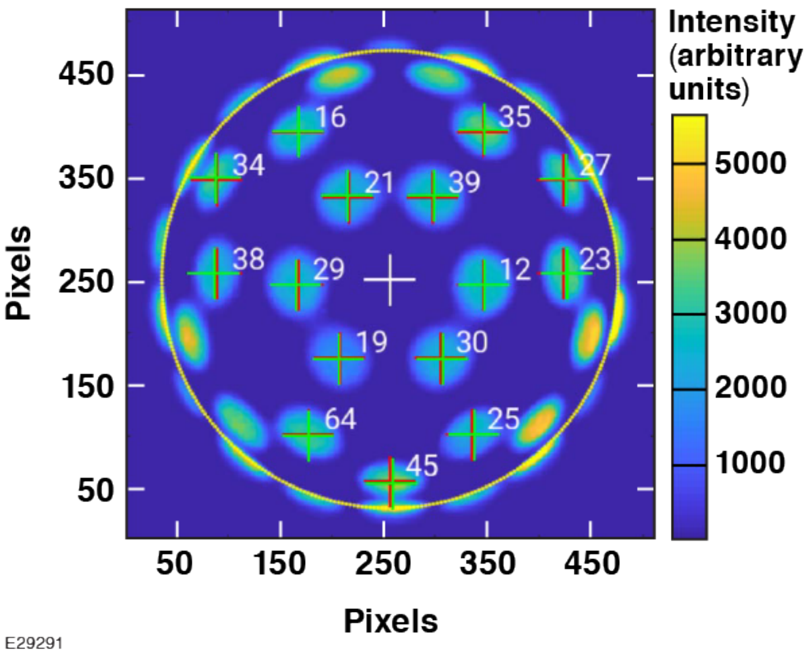
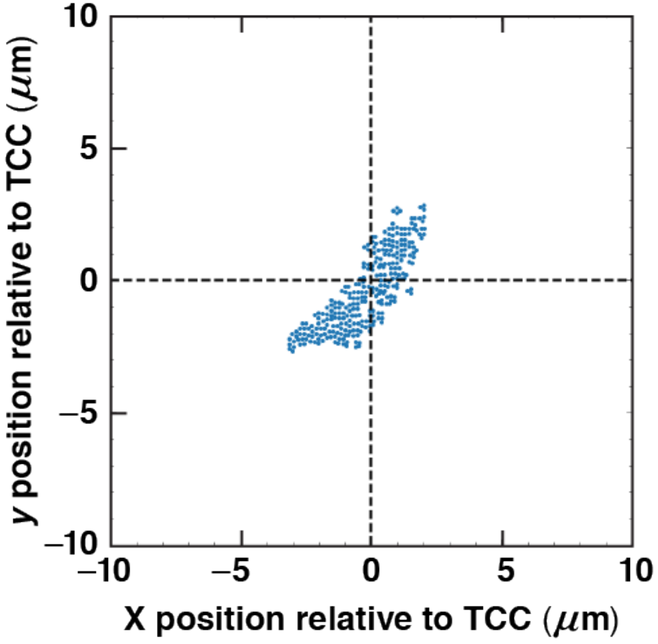
Target position and laser illumination uniformity (implosion inputs) are diagnosed for each experiment

Measured beam pointing target

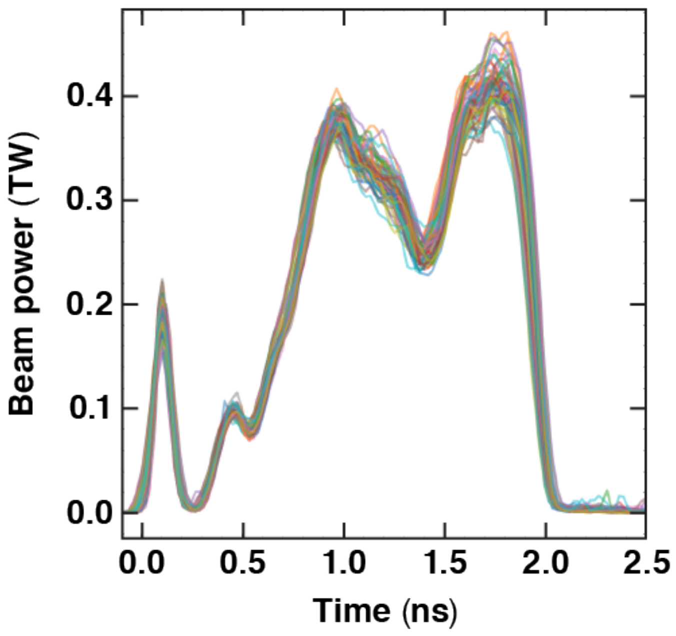


E29291

Target position measured with high-speed video*



Measured laser beam energy and timing

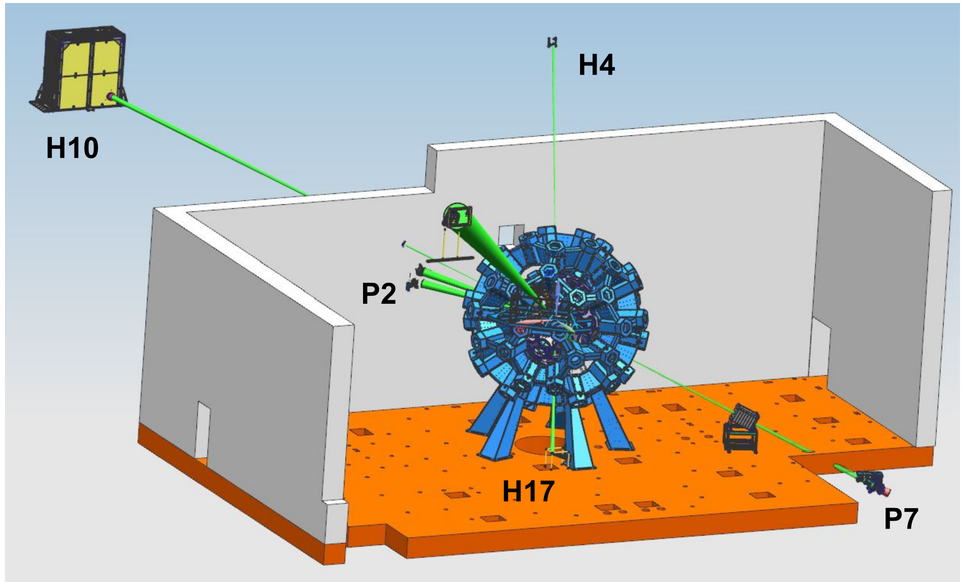


These measurements along with stagnation measurements are used to establish causal relationships between implosion inputs and outputs.

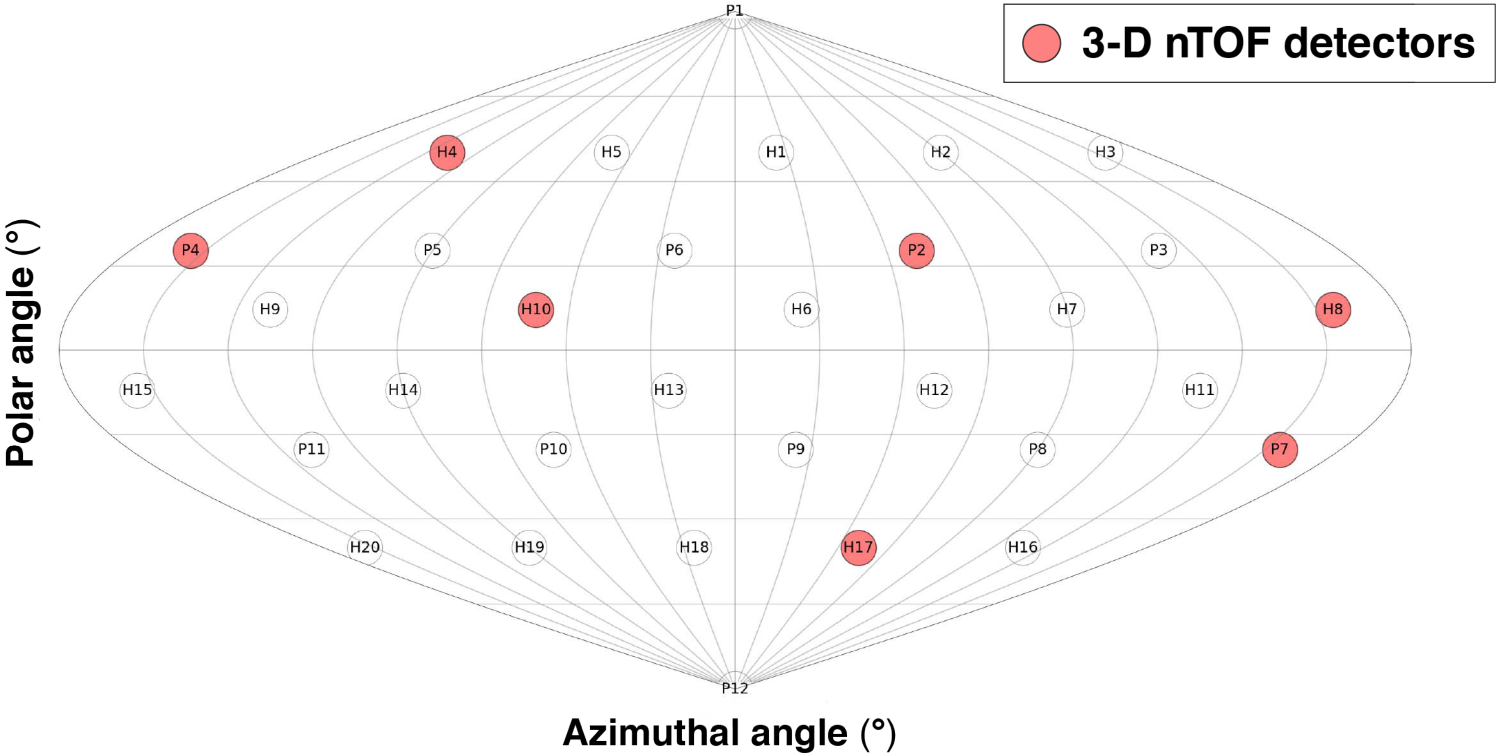
*Data acquired at 2 kHz sampling frequency
TCC: target chamber center

Advanced 3-D nuclear diagnostics have been deployed on OMEGA that measure the hot-spot velocity and ion temperature at stagnation

3-D nTOF detector suite*



nTOF detector configuration on OMEGA

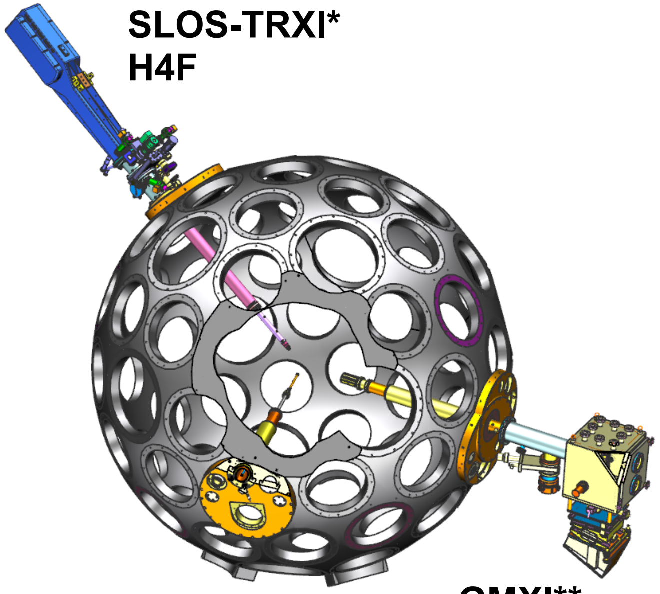


E29292

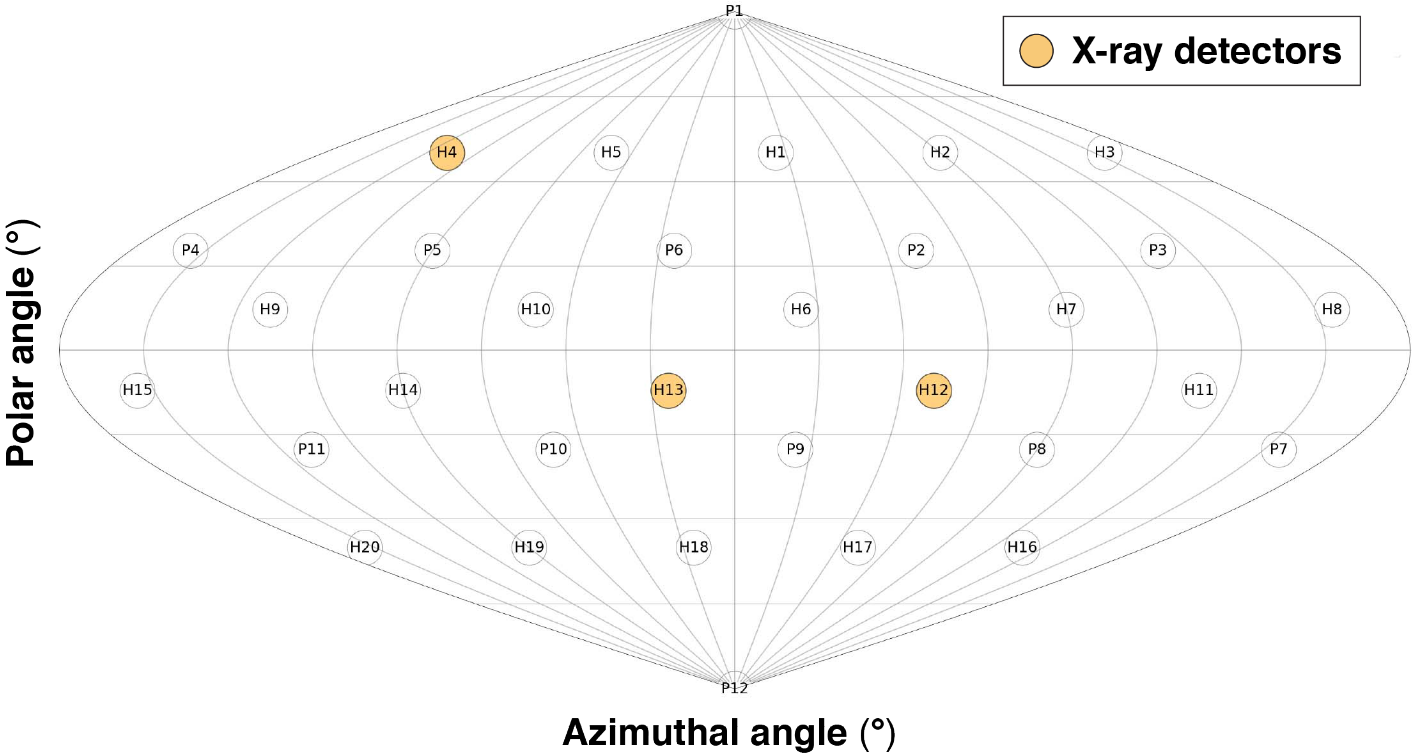
* O. M. Mannion *et al.*, Nucl. Instrum. Methods Phys. Res. A 964, 163774 (2020).
nTOF: neutron time of flight

Advanced 3-D x-ray*,** diagnostics have been deployed on OMEGA that image the hot-spot shape at stagnation

X-ray imagers*,**



X-ray detector configuration on OMEGA



E29293

* W. Theobald *et al.*, Rev. Sci. Instrum. 89, 10G117 (2018).
** F. J. Marshall *et al.*, Rev. Sci. Instrum. 88, 093702 (2017).

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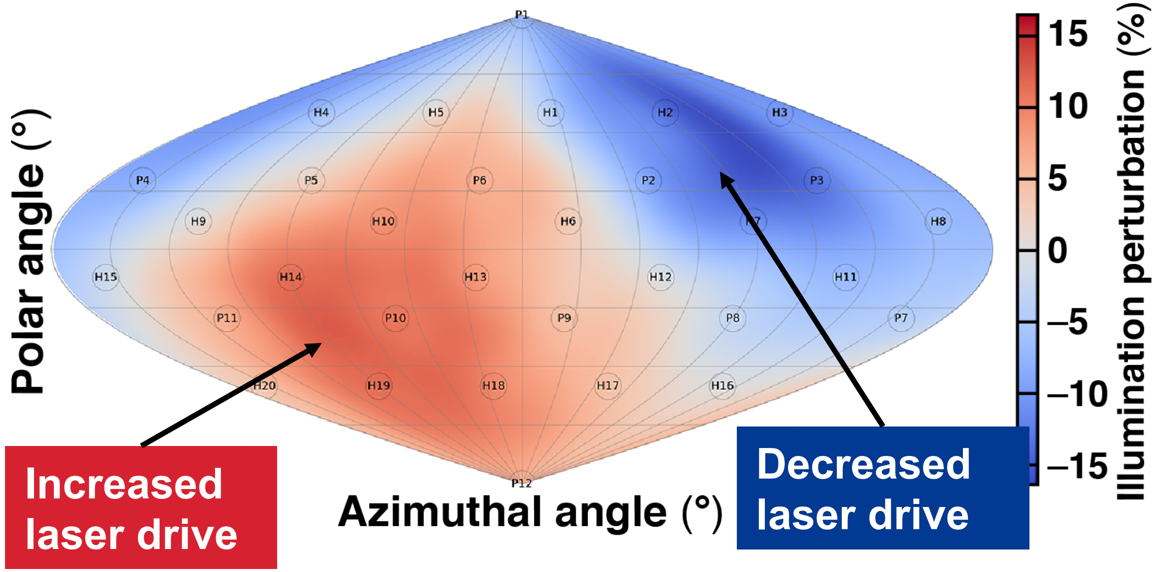
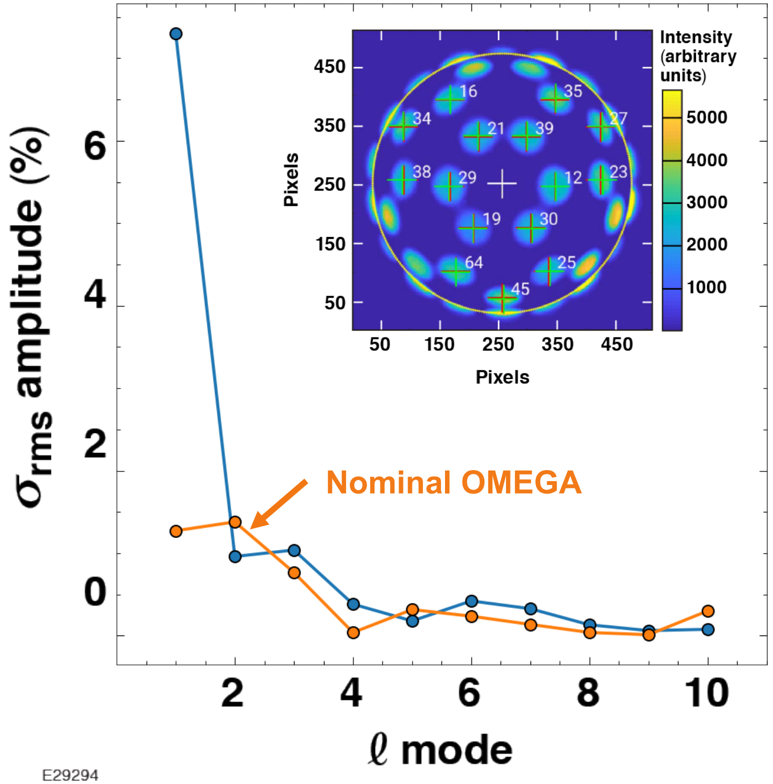
Large mode-1 drive asymmetries have been observed when large beam pointing errors exist

On-target laser illumination uniformity*

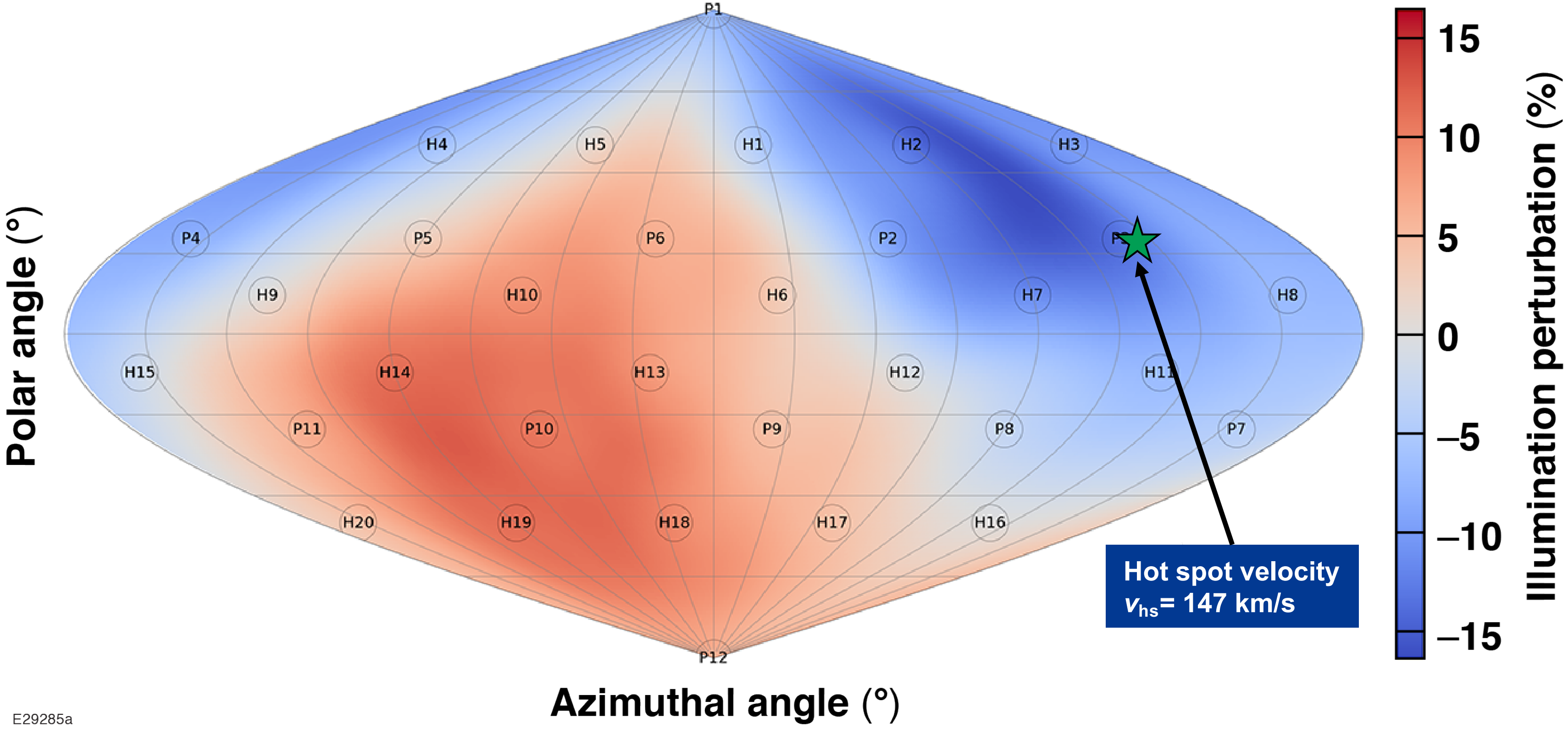


Measured beam pointing mode spectrum



*Includes energy balance, beam pointing, timing, target offset

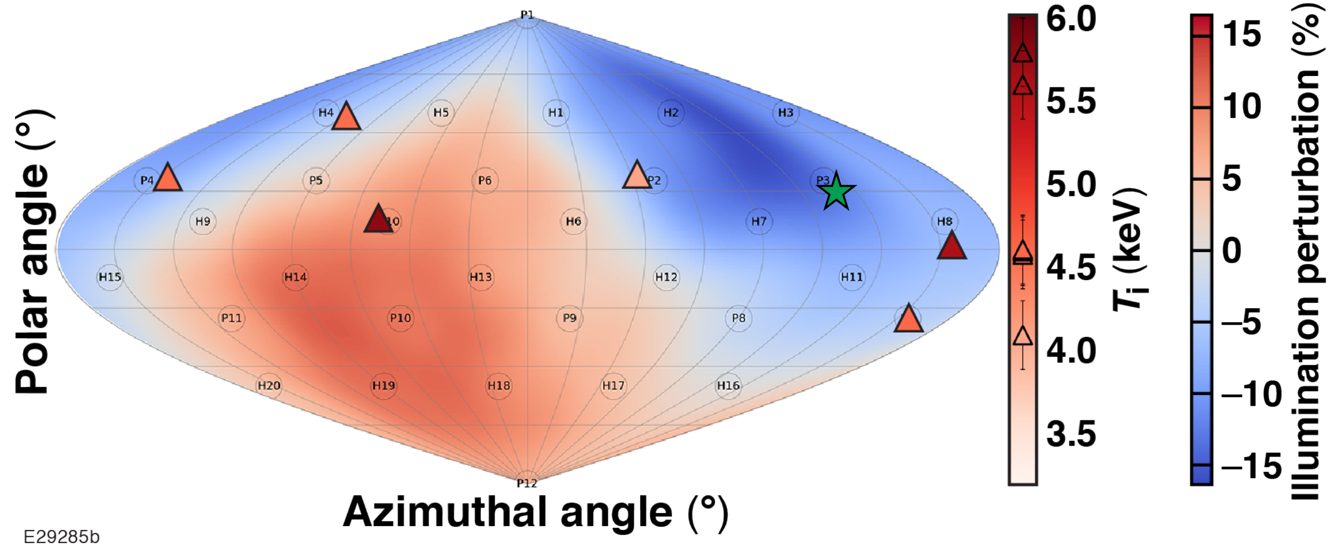
Implosions with large mode-1 asymmetries show large hot-spot velocities* (>100 km/s) and T_i asymmetries along the direction of the mode 1



The hot-spot velocity is along the direction of the drive deficit.

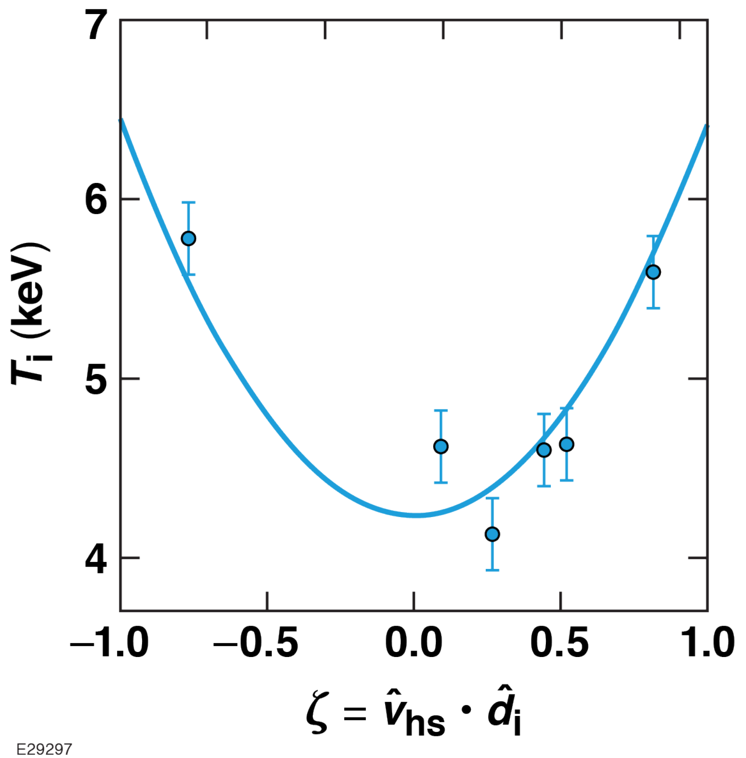
Implosions with large mode-1 asymmetries show large hot-spot velocities* (>100 km/s) and T_i asymmetries along the direction of the mode 1

On-target laser illumination uniformity*



E29285b

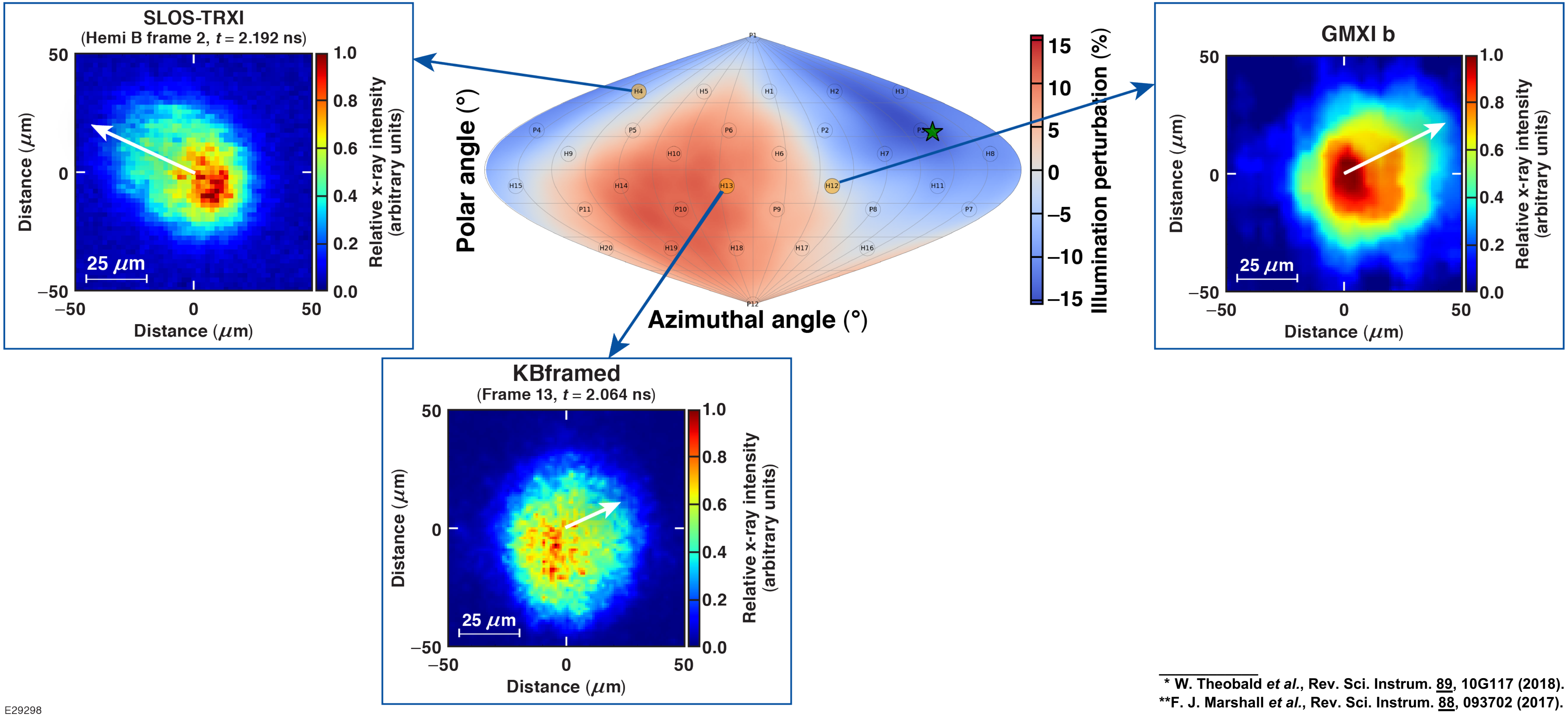
T_i versus projection along mode-1 direction



E29297

* Includes energy balance, beam pointing, timing, target offset

The elongation observed in hot-spot x-ray images is aligned with the mode-1 direction



* W. Theobald *et al.*, Rev. Sci. Instrum. 89, 10G117 (2018).
**F. J. Marshall *et al.*, Rev. Sci. Instrum. 88, 093702 (2017).

E29298

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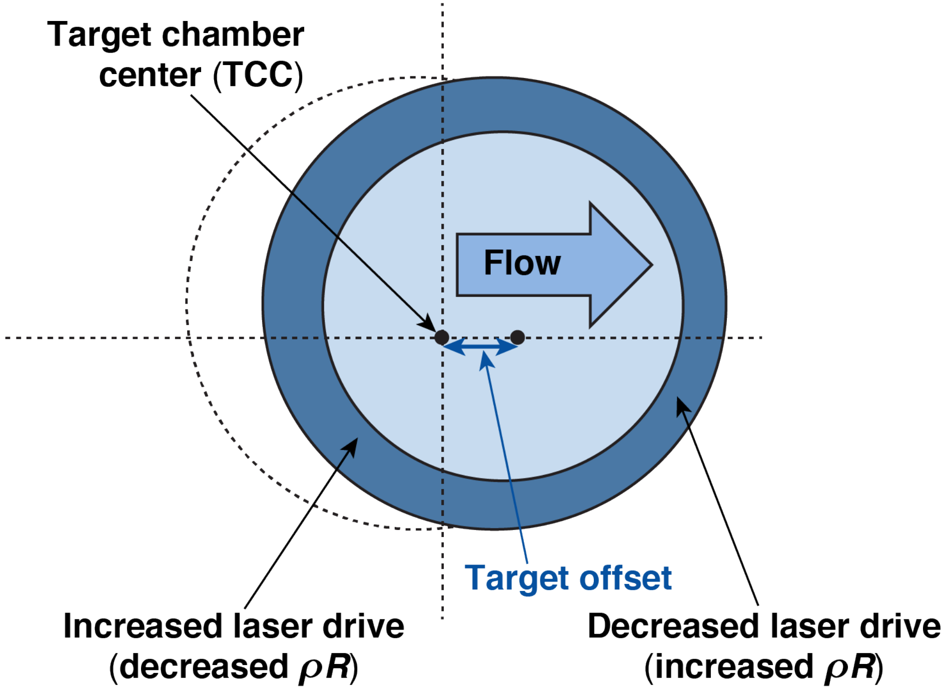
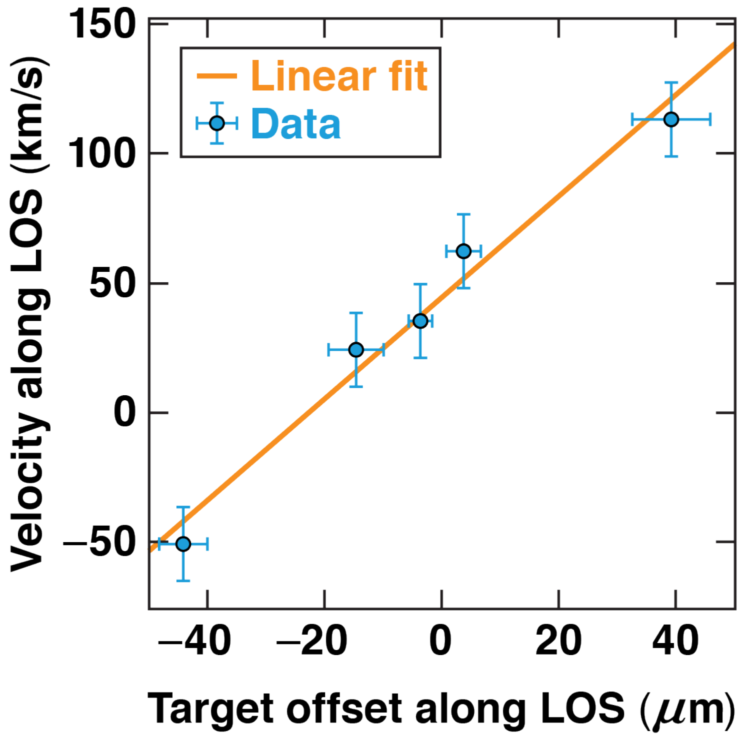
A linear relationship exists between the measured hot-spot velocity and the initial target position*,**



Response of target velocity to initial target offset



E29322

Initial target positioning can therefore be used to introduce or mitigate mode-1 asymmetries present in the initial drive.

* K. S. Anderson *et al.*, "Effect of Cross-Beam Energy Transfer on Target-Offset Asymmetry in Direct-Drive Inertial Confinement Fusion Implosions," accepted to Physics of Plasmas.

** M. Gatu Johnson *et al.*, Phys. Plasmas 27, 032704 (2020).

Mode-1 asymmetries can be suppressed by repositioning the target to a position derived from the hot-spot velocity measurements

- **Using hot-spot velocity measurements, an optimal target position can be derived to minimize the mode 1**

$$\vec{u} = \alpha(\vec{o} + \vec{r})$$

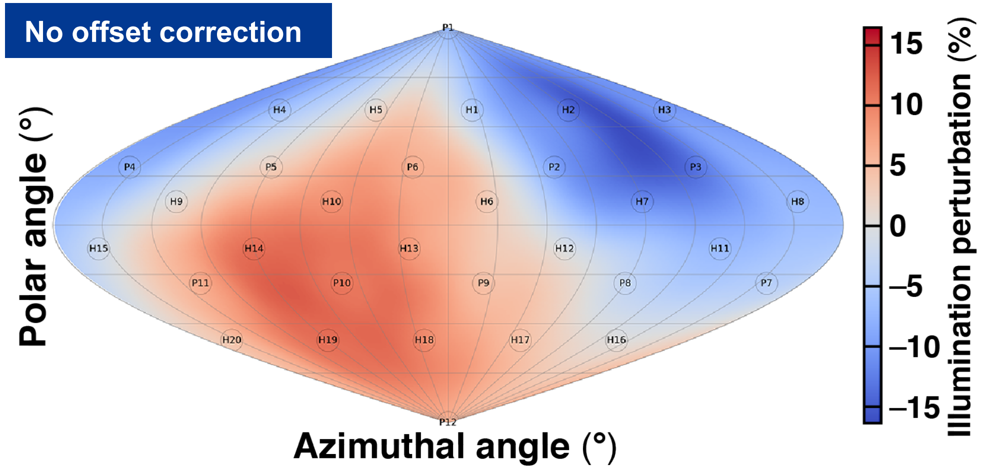
Hot-spot velocity → $\vec{u}$

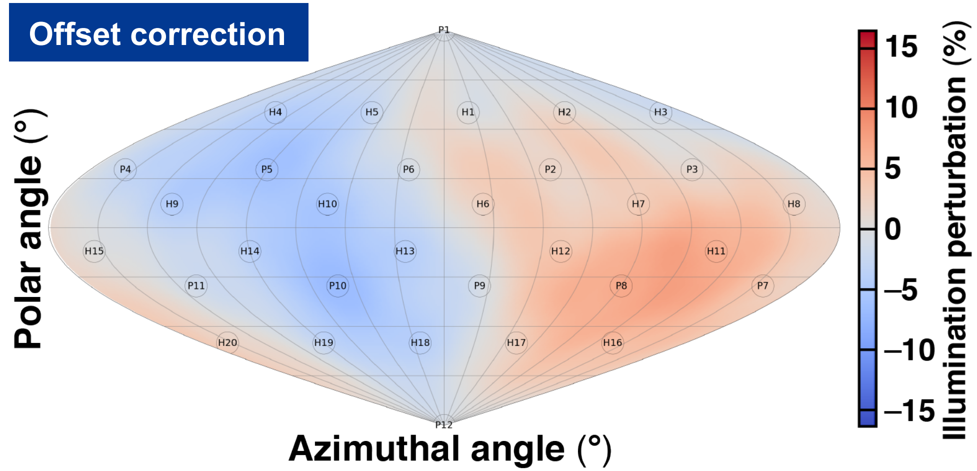
Offset to velocity conversion → α

Offset of unknown source → $\vec{o}$

High Speed Video Offset → $\vec{r}$

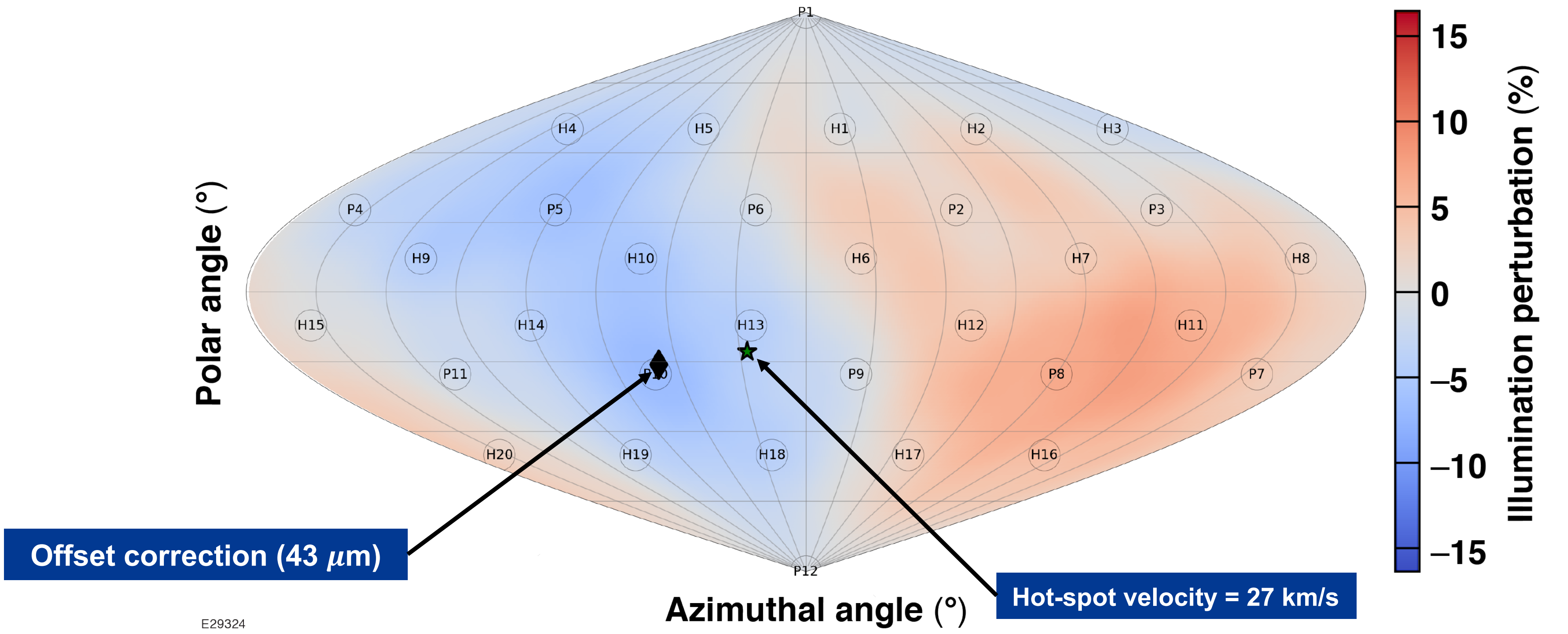
Laser illumination uniformity





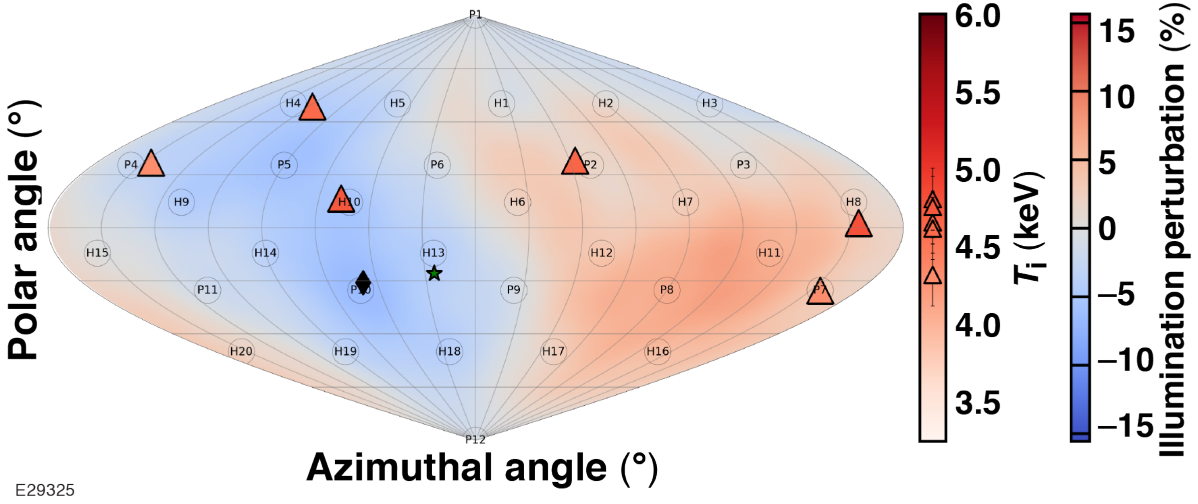
E29335

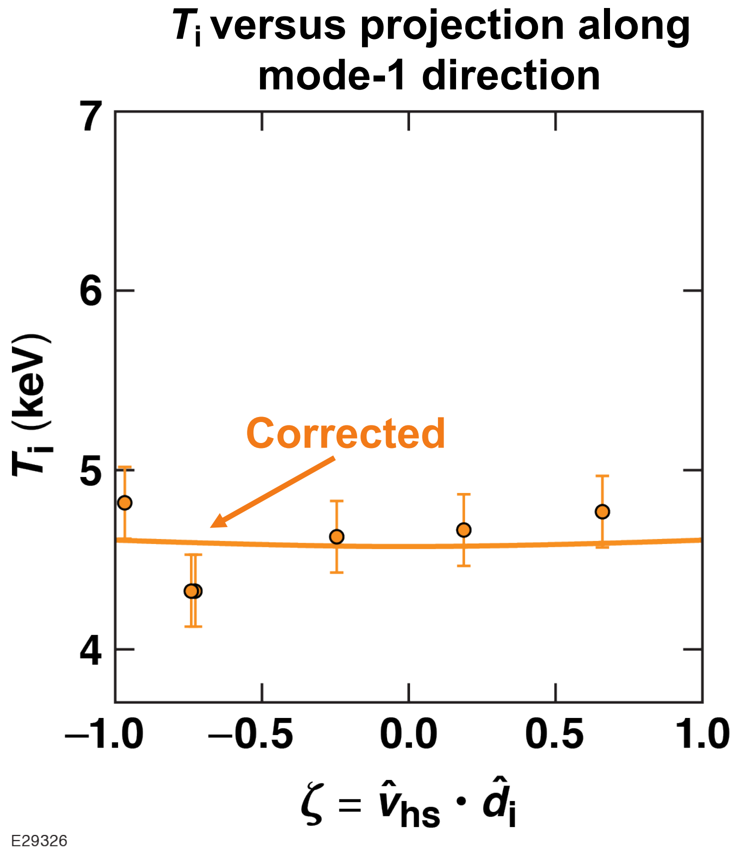
In experiments with large mode-1 drive asymmetry, repositioning the target to the derived location has been shown to reduce the asymmetry present at stagnation



With the target offset correction applied, the motion of the hot spot was reduced.

In experiments with large mode-1 drive asymmetry, repositioning the target to the derived location has been shown to reduce the asymmetry present at stagnation





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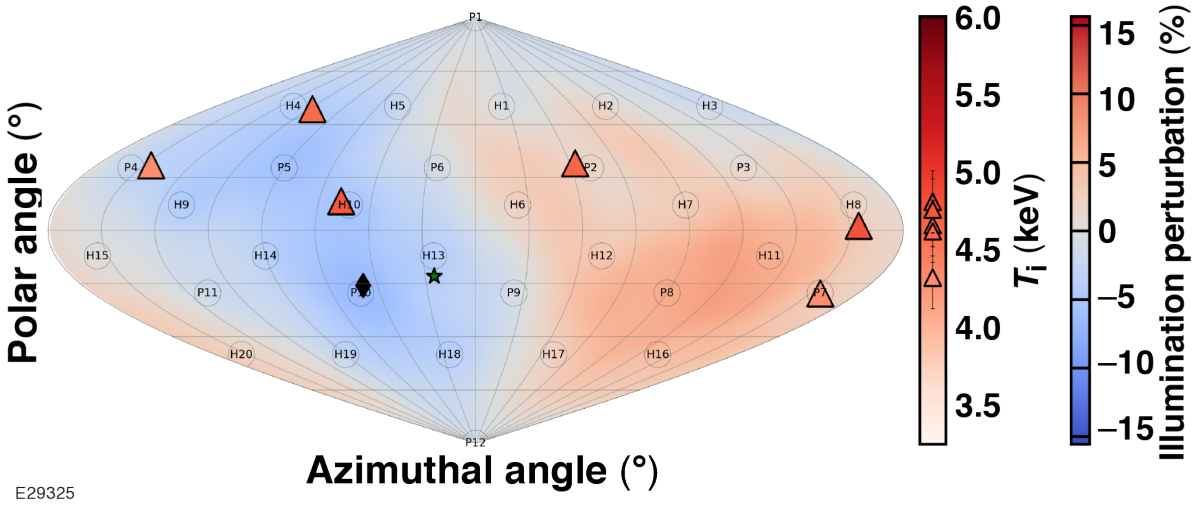
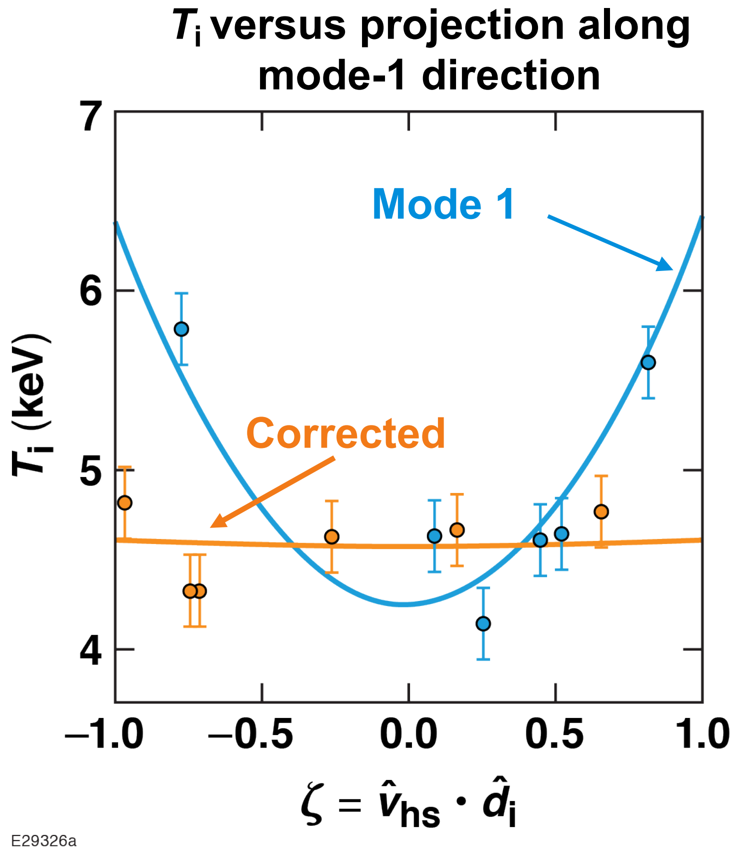
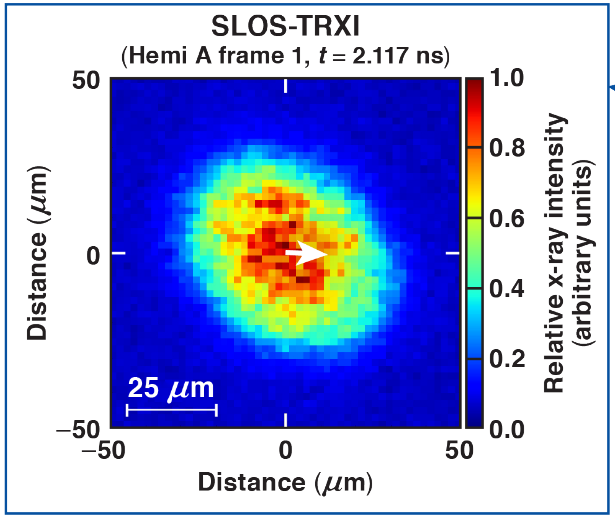
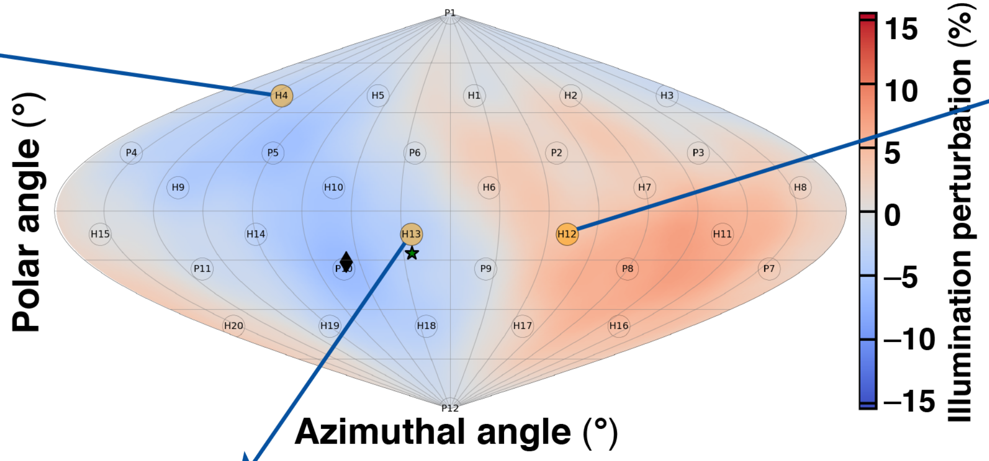
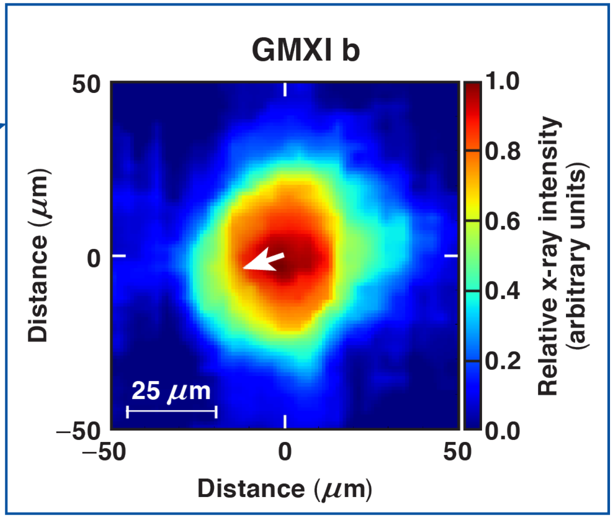


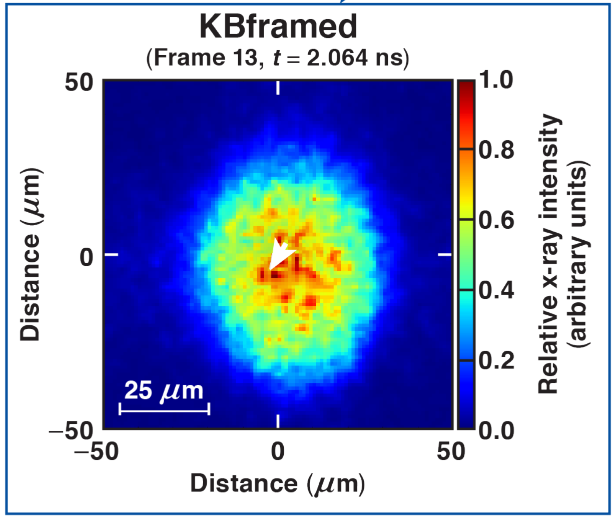


The hot-spot x-ray images are more symmetric in the absence of the mode-1 drive asymmetry





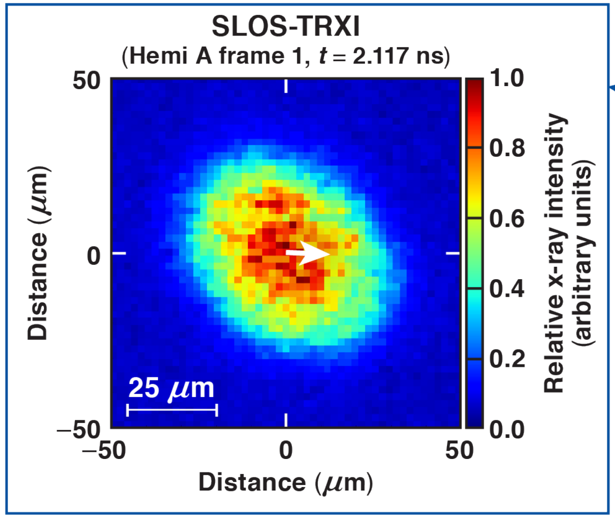


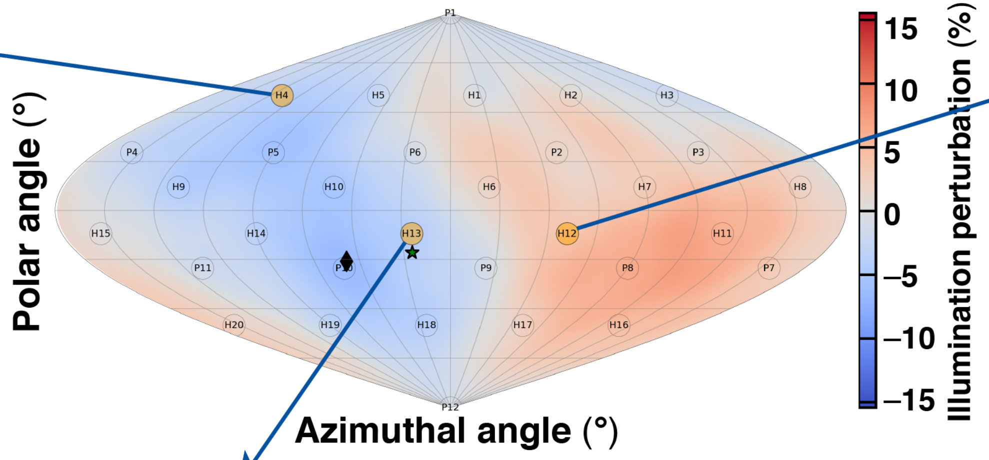


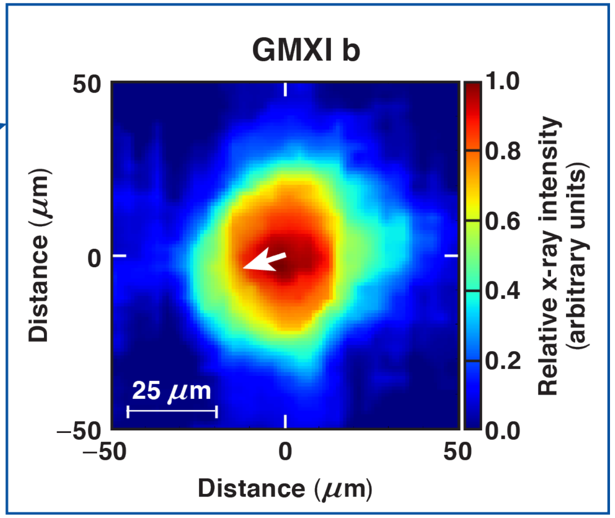
* W. Theobald *et al.*, Rev. Sci. Instrum. 89, 10G117 (2018).
**F. J. Marshall *et al.*, Rev. Sci. Instrum. 88, 093702 (2017).

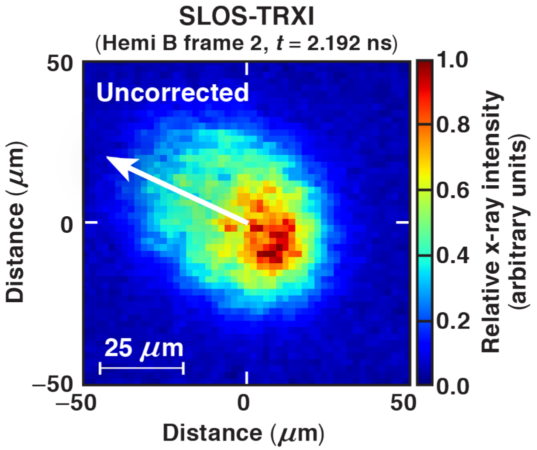
E29327

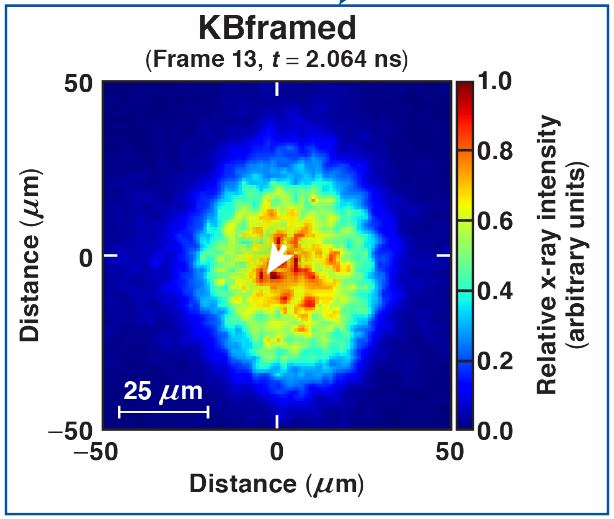
The hot-spot x-ray images are more symmetric in the absence of the mode-1 drive asymmetry

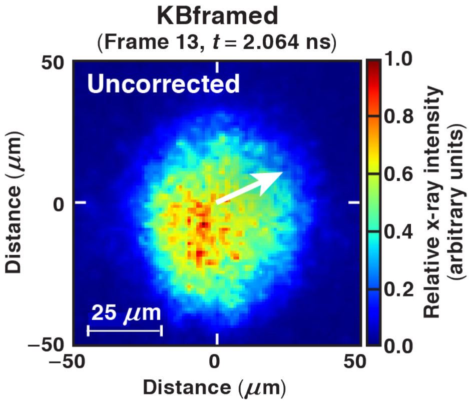


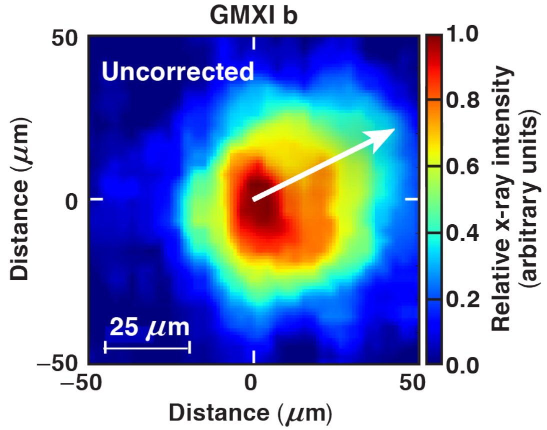












* W. Theobald *et al.*, Rev. Sci. Instrum. 89, 10G117 (2018).
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E29327a

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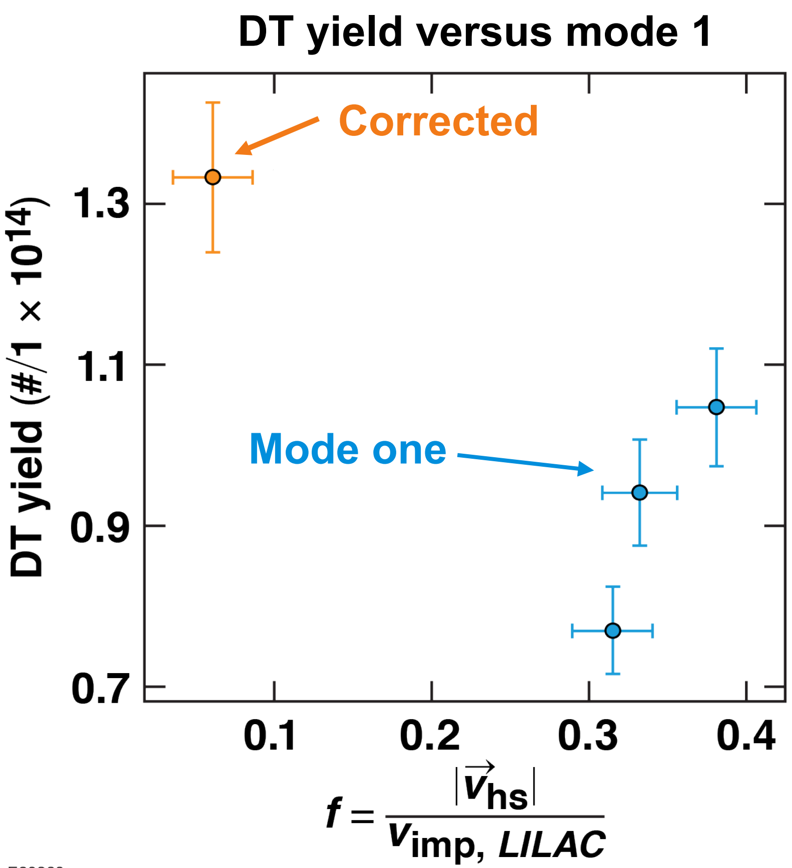
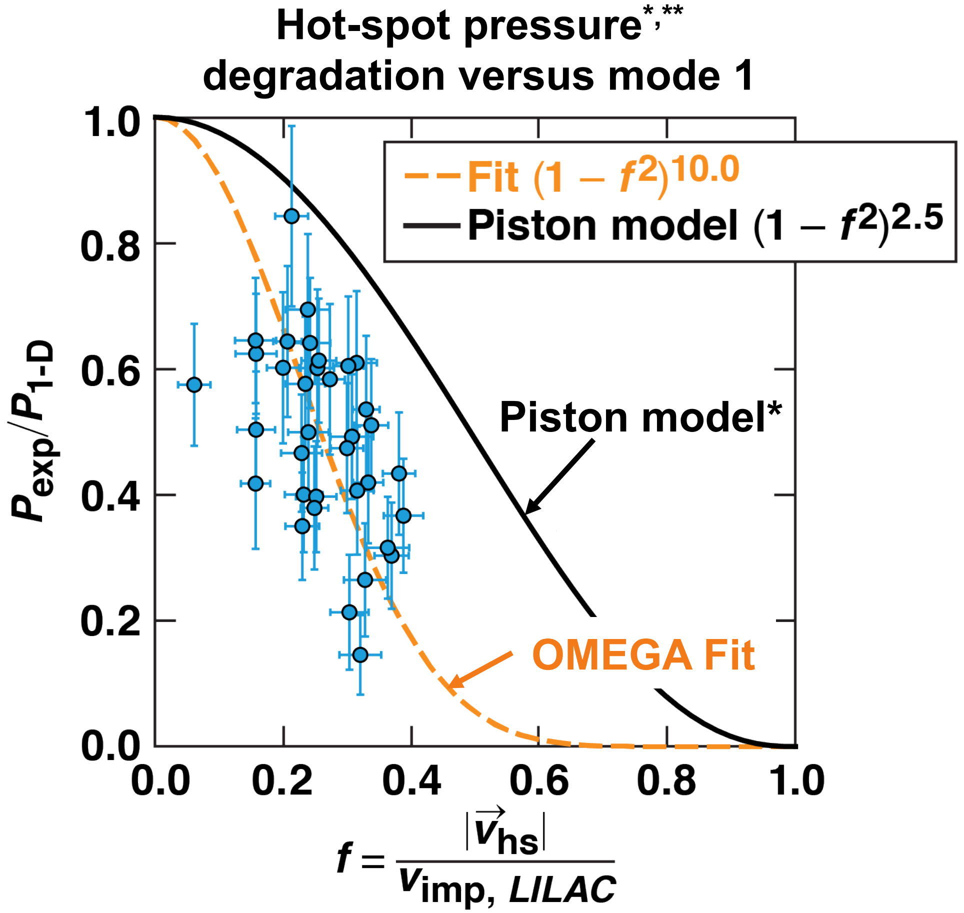
Causal relationships between $\ell = 1$ asymmetries and implosion performance at stagnation have been observed with 3-D nuclear and x-ray diagnostics on OMEGA



E29328



* O. A. Hurricane *et al.*, Phys. Plasmas 27, 062704 (2020).
** S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016), 059903(E) (2016).

3-D diagnostic information is now being incorporated into statistical modeling to help understand laser-drive drive-implosion performance*,**

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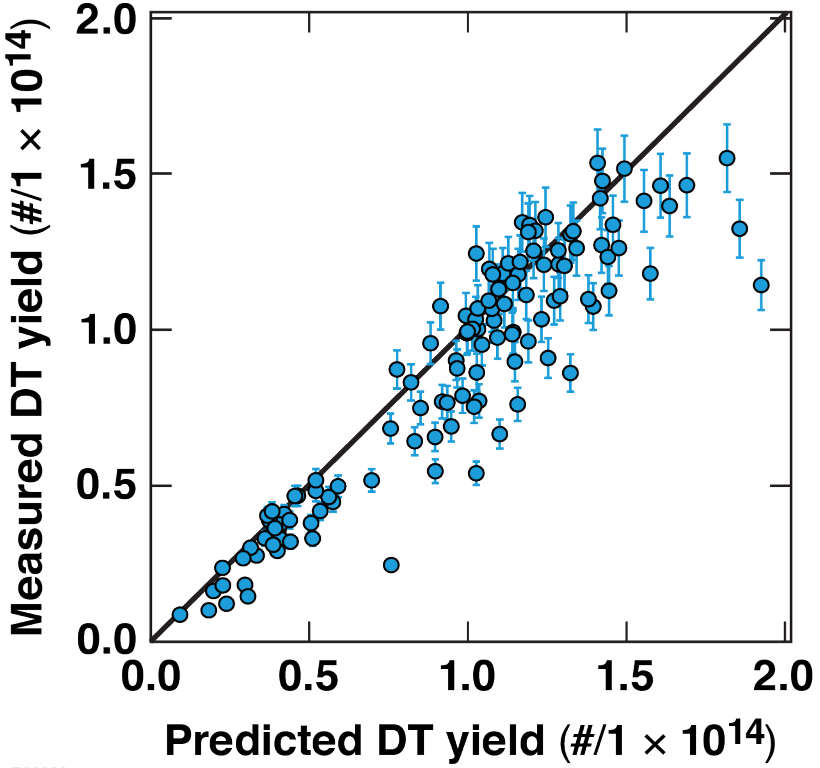
Post-shot statistical predictions (1-D inputs)



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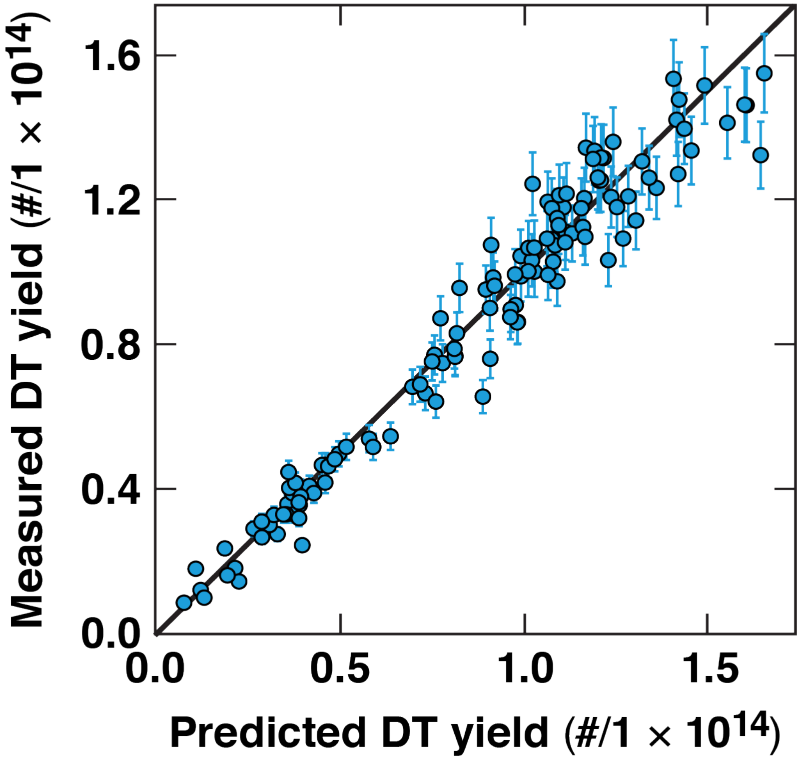
3-D diagnostic information

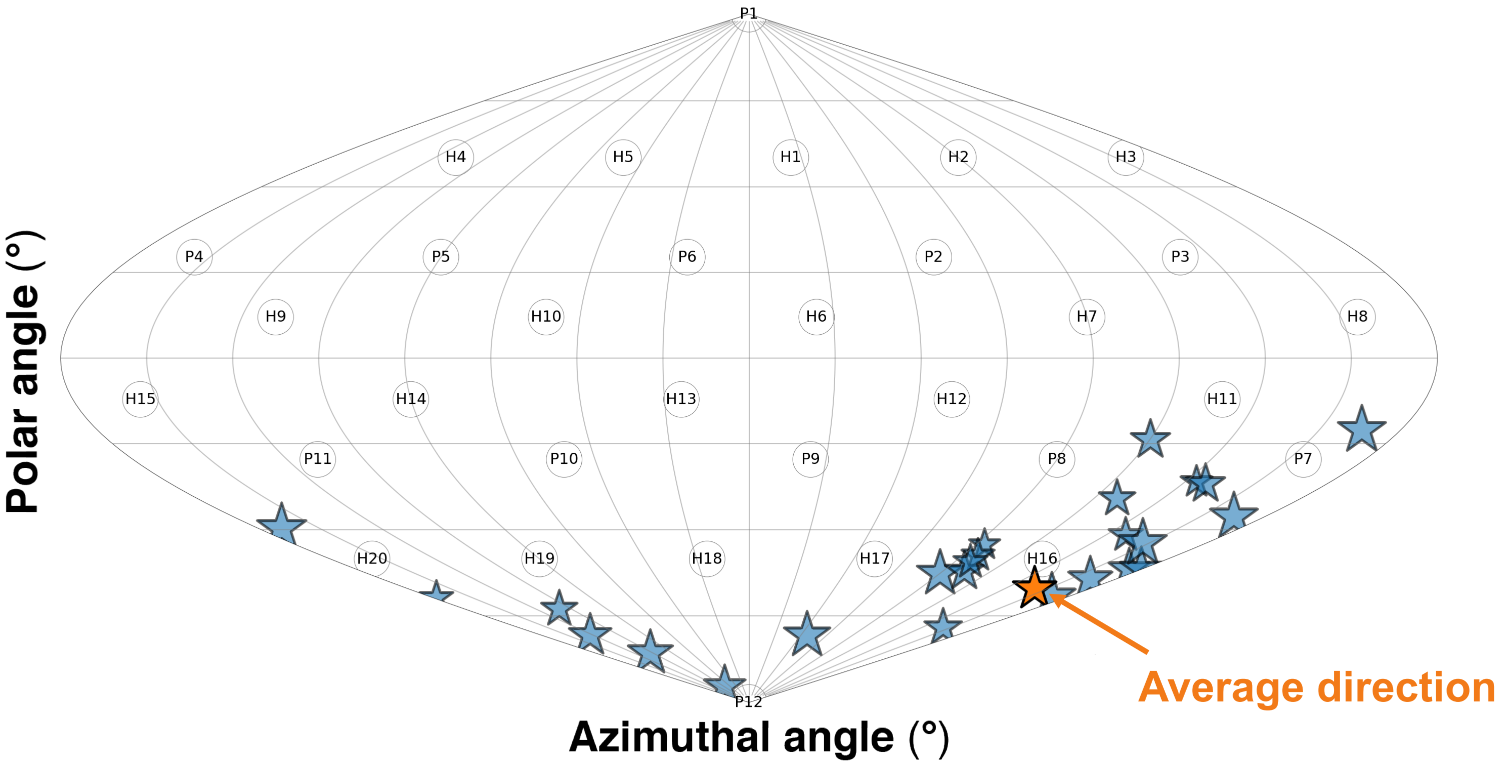
$$\mathrm{YOC}_{\ell=1} \approx \mathrm{Min}\left[1, 1.14\left(\frac{T_{\min}}{T_{\max}}\right)\right]^{1.55}$$

Post-shot statistical predictions (1-D + 3-D inputs)



* V. Gopalaswamy *et al.*, Nature 565, 581 (2019).
** A. Lees, TI01.00006, this conference (invited);

Hot velocity measurements across an ensemble of nominal cryogenic implosions suggest the presence of a systematic mode one asymmetry in our implosions



We are investigating potential systematic asymmetry sources* such as the target mount, ice non-uniformity, mechanical drifts in OMEGA

* H.G. Rinderknecht, et. al., Phys. Rev. Lett. 124, 145002 (2020).

Summary

Causal relationships between $\ell = 1$ asymmetries and implosion performance at stagnation have been observed with 3-D nuclear and x-ray diagnostics on OMEGA

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- Mode-1 implosion asymmetries can be varied through initial target positions and laser beam pointing
- Implosions with large seeded mode-1 asymmetries show large hot-spot velocities[*,**] (>100 km/s) and apparent T_i asymmetries along the direction of the mode 1
- The asymmetry observed in hot-spot x-ray images is aligned with the mode-1 direction
- Mode one drive asymmetries are observed to decrease implosion performance
  - hot-spot pressure degradation is strongly related to mode-1 asymmetries
  - accurate post-shot predictions require statistical modeling[†] that account for mode-1 asymmetries

Three-dimensional diagnostic measurements are identifying steps that can be taken to improve symmetry and integrated performance of laser-direct-drive implosions.

* O. M. Mannion *et al.*, Nucl. Instrum. Methods Phys. Res. A 964, 163774 (2020).
**R. Hatarik, Rev. Sci. Instrum. 89, 10I138 (2018).
† A. Lees, TI01.00006, this conference (invited).

Related talks during this conference

- B MacGowan. TO07:2: “Quantifying sources of low mode 3D asymmetries in indirect drive implosions at the National Ignition Facility”
- R. Nora TO07:5: “On the sensitivity of bulk hot spot motion in inertial confinement fusion implosions under the presence of x-ray flux asymmetries “
- J. Milovich TO07:7: “Non-concentricity of HDC ablator layers can provide additional sources of mode-1 asymmetries on implosions at the National Ignition Facility"
- D.J. Schlossberg TO07:14: “How our physics understanding changes when we move from 2D to 3D measurements in ICF plasmas”
- D. Casey VI01:3: “The impact of low-mode areal-density non-uniformities in indirect-drive implosions at the National Ignition Facility”
- B. Lahmann GO11:14: “Signatures of hot-spot asymmetries in secondary DT neutron spectra in NIF implosions”
- C. Forrest BO09:3: “Evaluating the Residual Kinetic Energy in Direct-Drive Cryogenic Implosions on OMEGA”