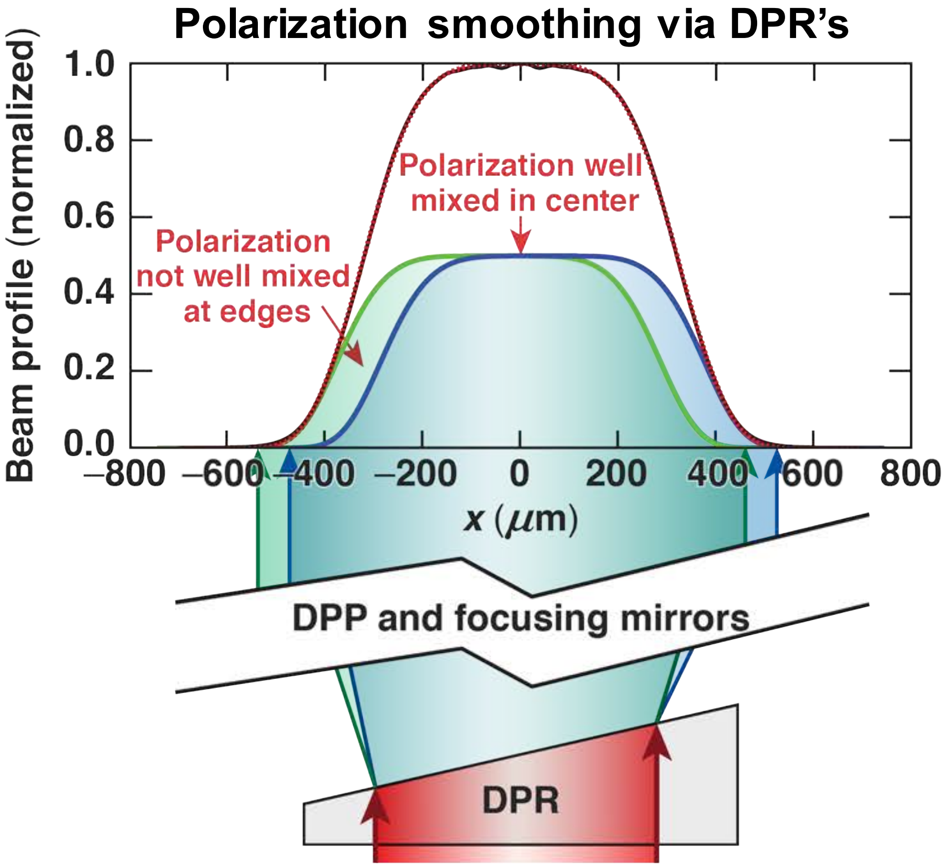
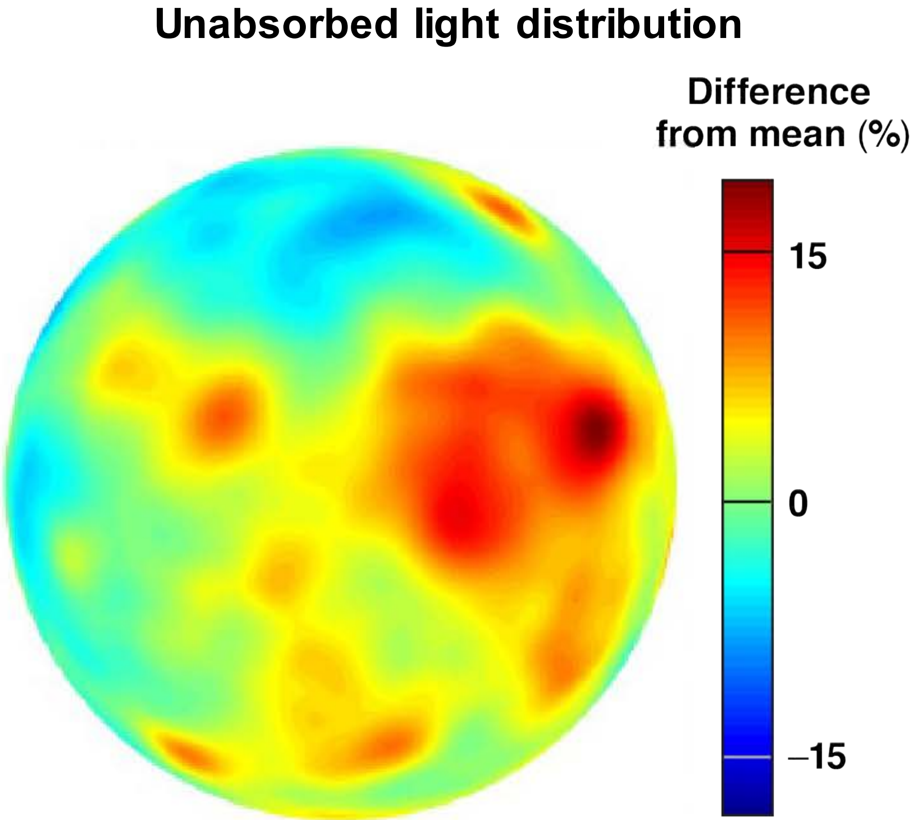
Nonuniformity in Direct-Drive Implosions Caused by Polarization Smoothing





D. H. Edgell
University of Rochester
Laboratory for Laser Energetics

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Division of Plasma Physics
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Summary

Polarization-dependent cross-beam energy transfer (CBET) causes significant scattered-light nonuniformity in direct-drive implosions on OMEGA

UR LLE

- Uniform laser energy absorption is essential for successful laser-direct-drive inertial confinement fusion
- A growing body of evidence (including hot-spot flows, ion-temperature asymmetry, and nonuniform scattered light) suggests OMEGA implosions are more asymmetric than predictions
- By measuring the intensity and polarization of light scattered from individual beams, we have identified OMEGA's polarization smoothing via distributed polarization rotators (DPR's) as one previously unrealized source of nonuniformity
- Three-dimensional modeling of polarization-dependent CBET for OMEGA's beams accounting for the DPRs is consistent with the scattered-light observations
- Fabricating and deploying new DPR's that mitigate this source of asymmetry are presently under review and might be implemented in as soon as a year

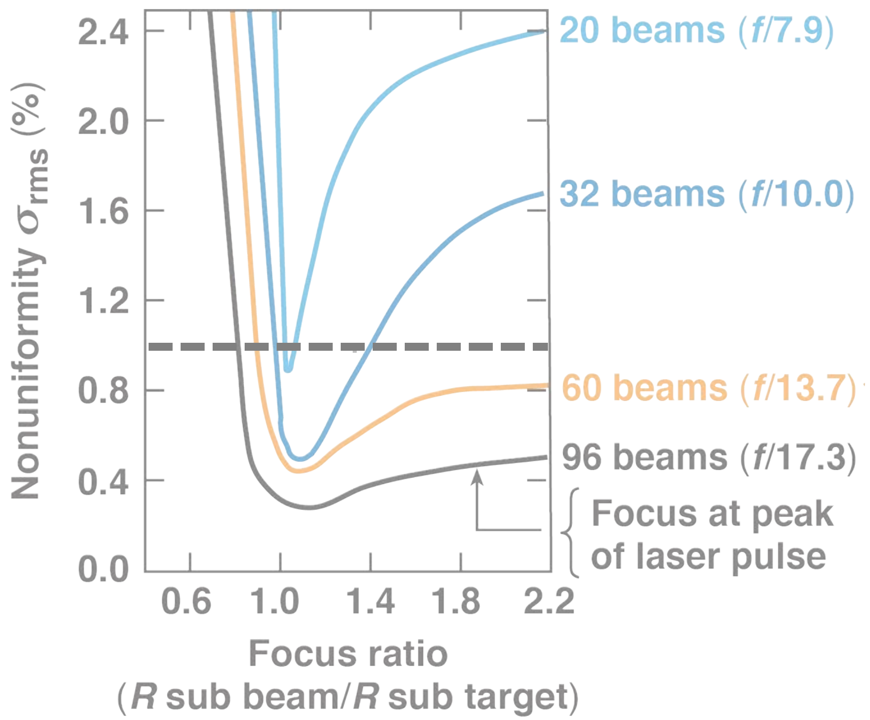
Collaborators

A. Colaïtis,[2] R. S. Craxton,[1] R. K. Follet,[1] M. J. Guardalben,[1] A. Kalb,[1] J. Katz,[1] J. Kwiatkowski,[1]
O. M. Mannion,[3] P. B. Radha,[1] A. Shvydky,[1] C. Stoeckl,[1] D. Turnbull,[1] and D. H. Froula[1]

[1]LLE
[2]Université de Bordeaux, France
[3]Sandia National Lab, Albuquerque NM

It is generally considered that high-convergence laser-direct-drive implosions require absorption with a nonuniformity <1% rms for successful fusion*

OMEGA uses 60 overlapping laser beams to achieve quasi-uniform absorption**



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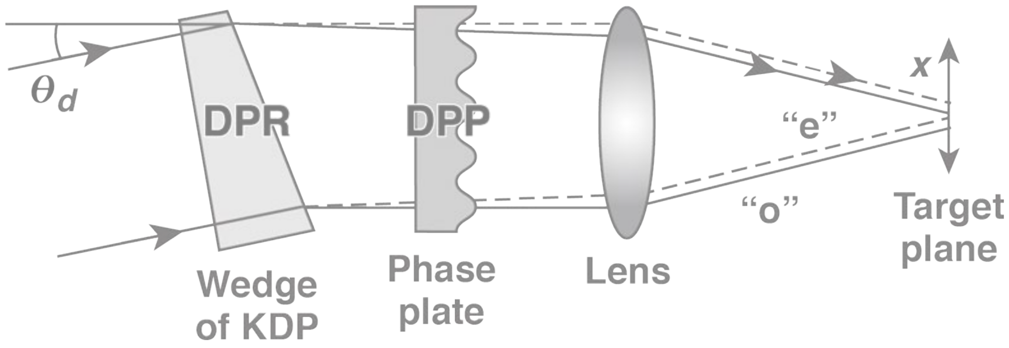
Individual beams are smoothed by*

- Distributed phase plates (DPPs)
- Smoothing by spectral dispersion (SSD)
- Polarization smoothing using distributed polarization rotators (DPRs) †



TC11871

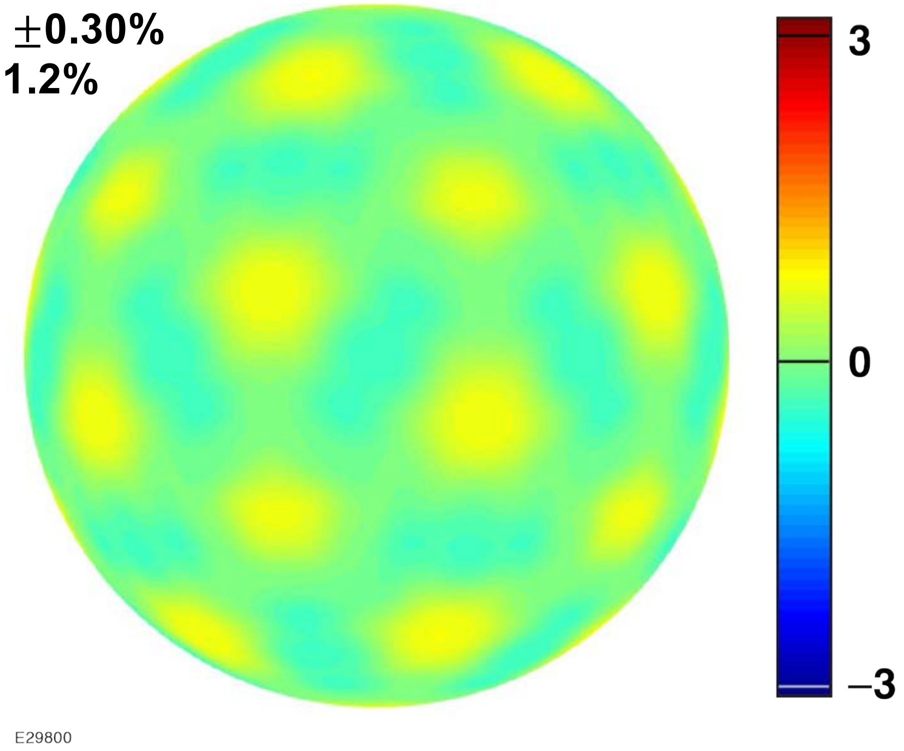
* R. S. Craxton *et al.*, Phys. Plasmas 22, 110501 (2015).
** LLE Review Quarterly Report 19, 120 (1984).
† T. R. Boehly *et al.*, J. Appl. Phys. 85, 3444 (1999).

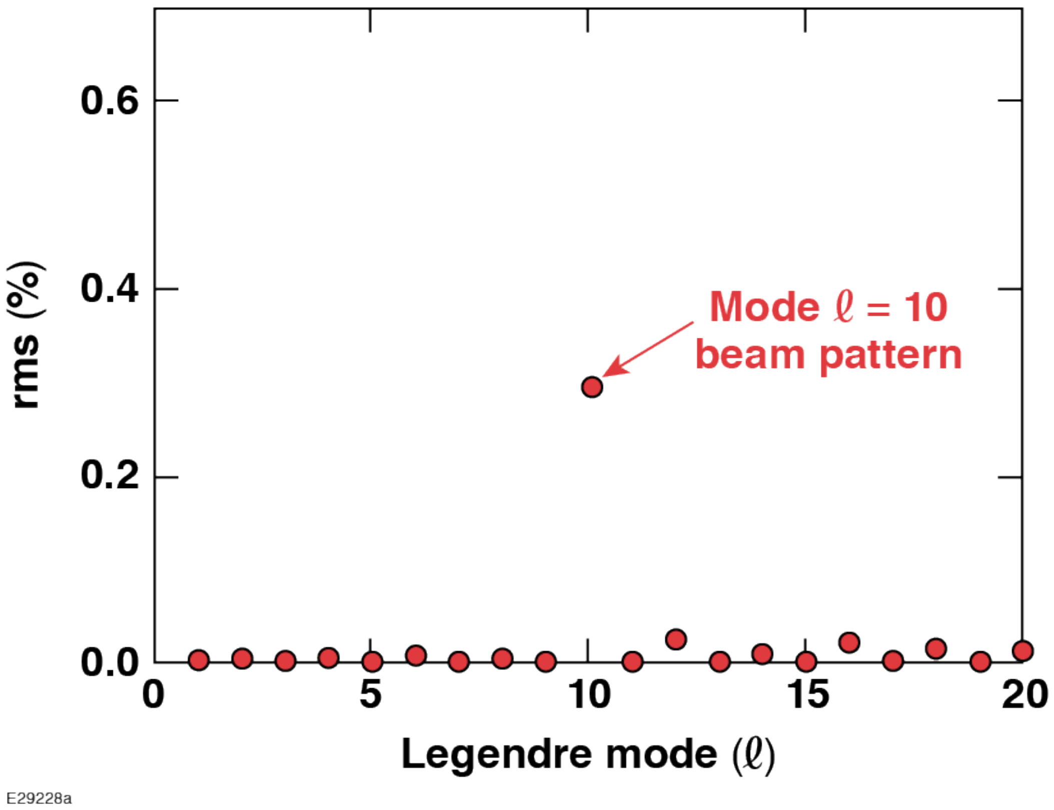
OMEGA's uniform illumination leads to very uniform predictions for laser energy deposition in the plasma via inverse bremsstrahlung absorption

Predicted time-integrated total absorbed

$$\int P_{\text{abs}}(\theta, \varphi, r, t)\mathbf{d}r\mathbf{d}t$$

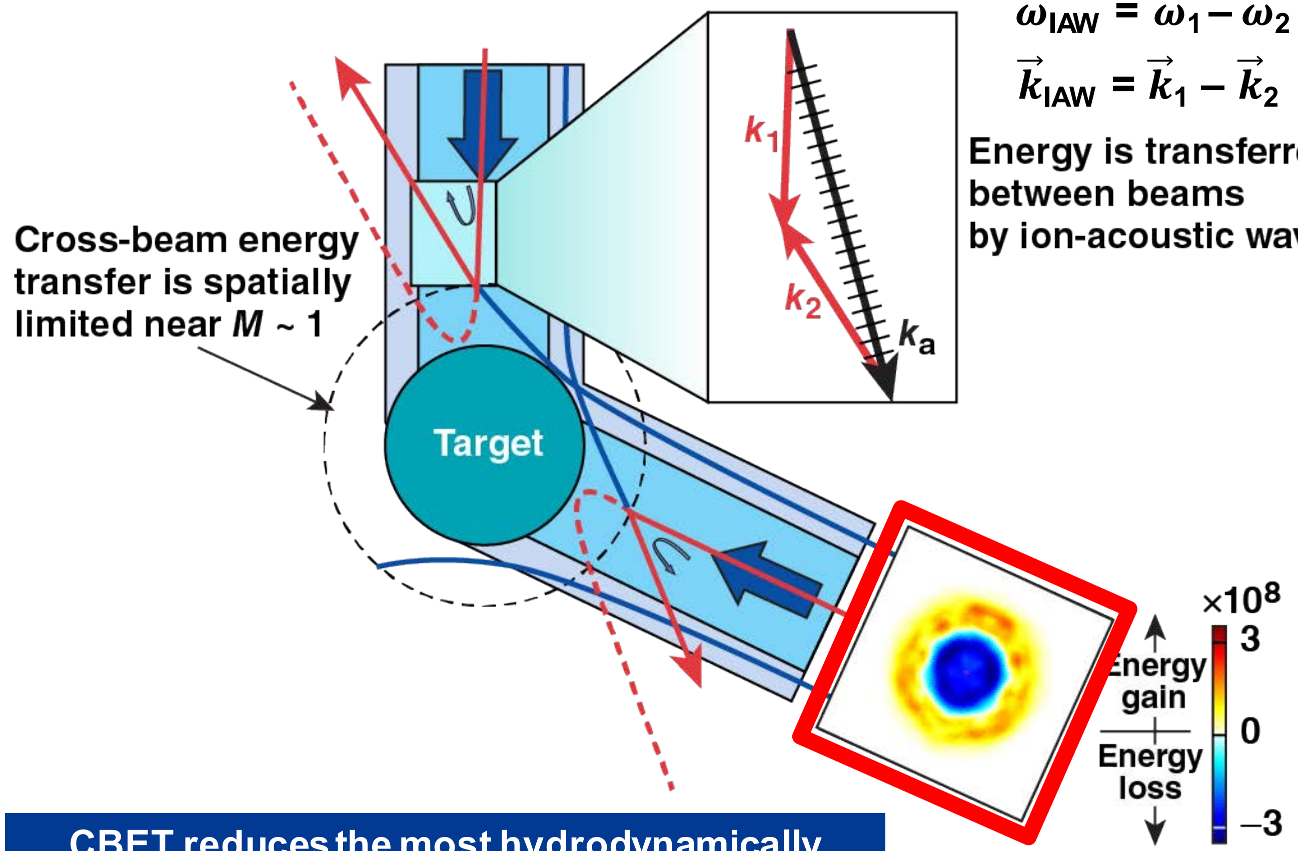
rms: ±0.30%
P-V: 1.2%





OMEGA 60-beam cryo implosion: shot 97580

Cross-beam energy transfer (CBET) reduces the total absorption

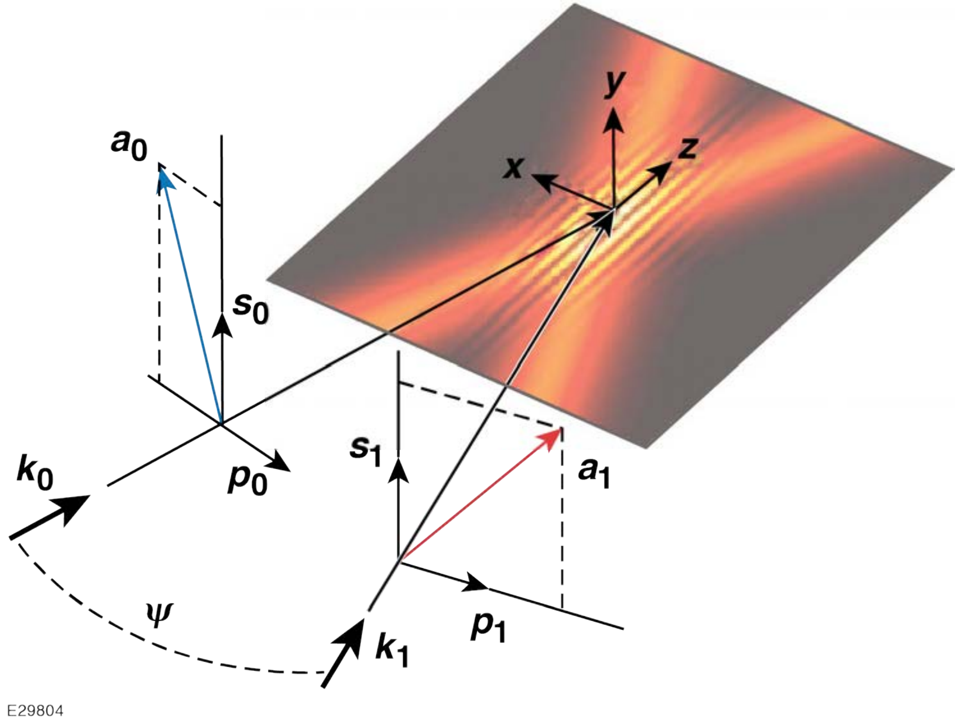


$$\omega_{\mathrm{IAW}} = \omega_1 - \omega_2$$

$$\vec{k}_{\mathrm{IAW}} = \vec{k}_1 - \vec{k}_2$$

Energy is transferred between beams by ion-acoustic waves

$$\sum_s dE_{\mathrm{CBET}}$$



CBET reduces the most hydrodynamically efficient portion on the incident laser beams.

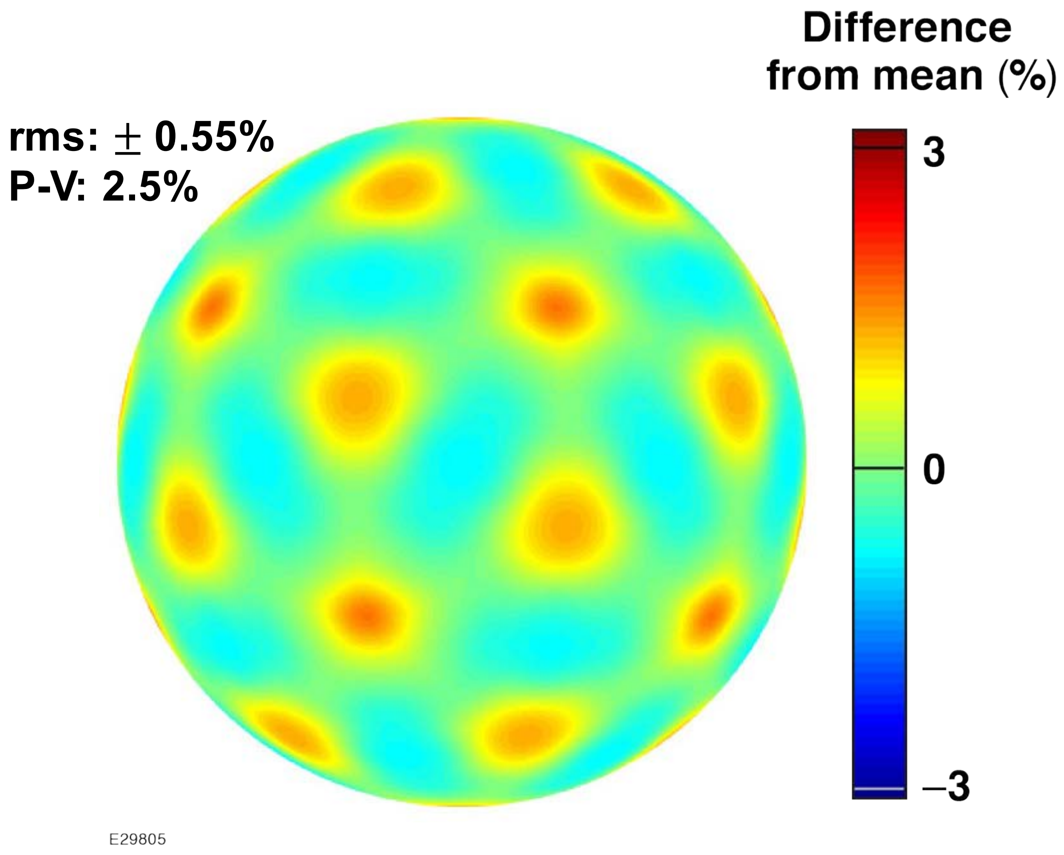
CBET is highly dependent on the relative polarizations of the crossing beams, but a simple factor can be used to account for polarization effects if each beam consists of two equal but orthogonal polarizations*

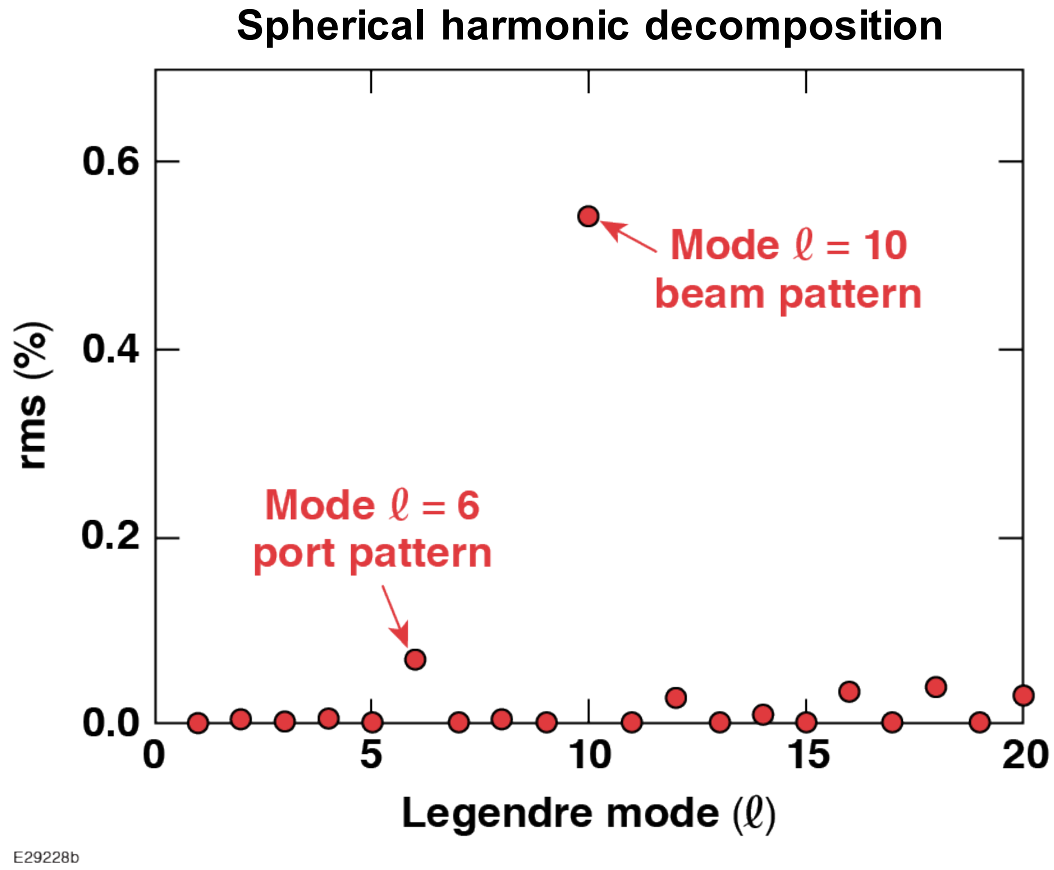
$$\Theta = \frac{1}{4}\left(1 + \cos^2\theta_2\right)$$

- P. Michel *et al.*, Phys. Plasmas 20, 056308 (2013).
  P. Michel *et al.*, PRL 113, 205001 (2014)

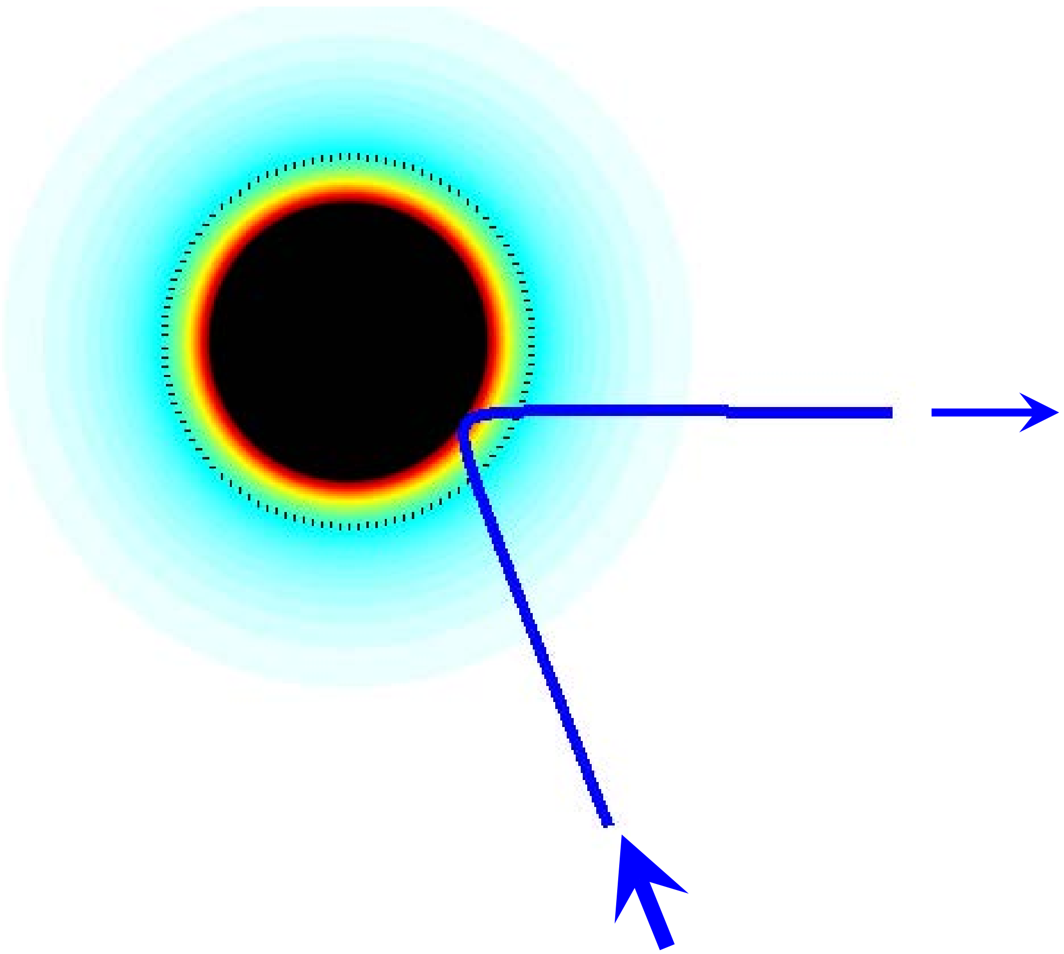
The CBET absorption distribution is still predicted to be symmetric about the OMEGA beam/port pattern for a symmetric implosion

Predicted time-integrated total absorbed energy
$\int P_{\text{abs}}(\theta, \varphi, r, t)\,\mathrm{d}r\mathrm{d}t$





Since absorbed energy cannot be directly measured, it is inferred by measuring the amount of unabsorbed light that leaves the target



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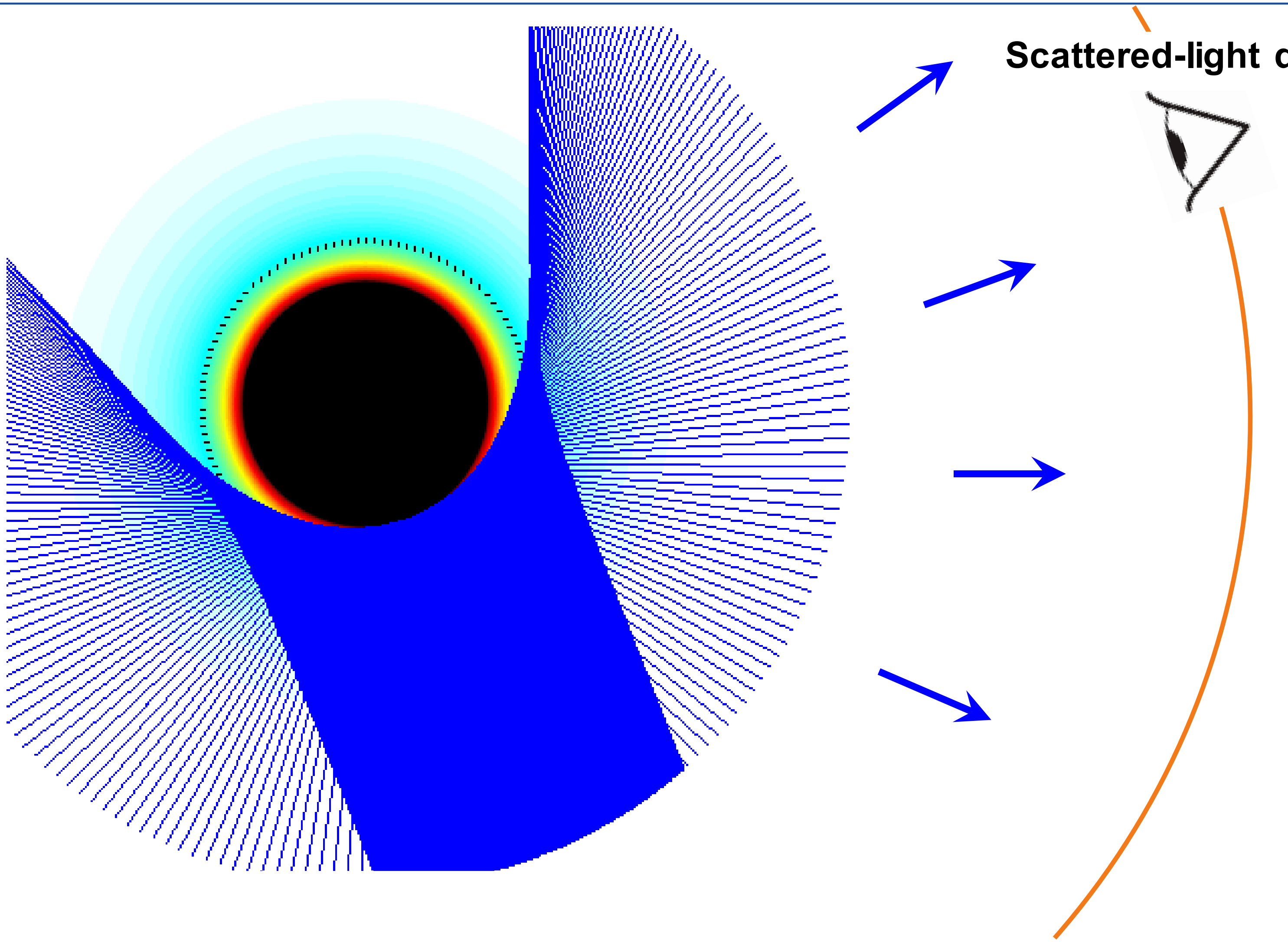
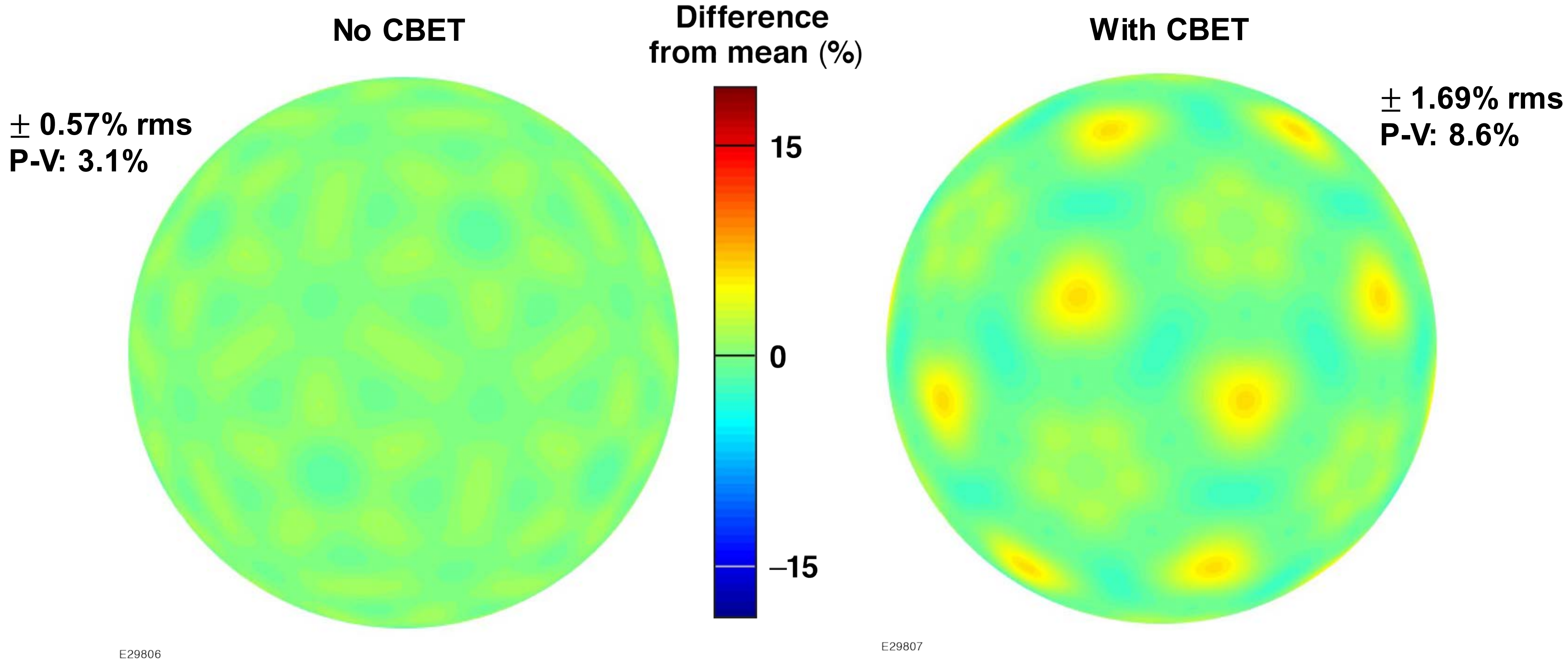


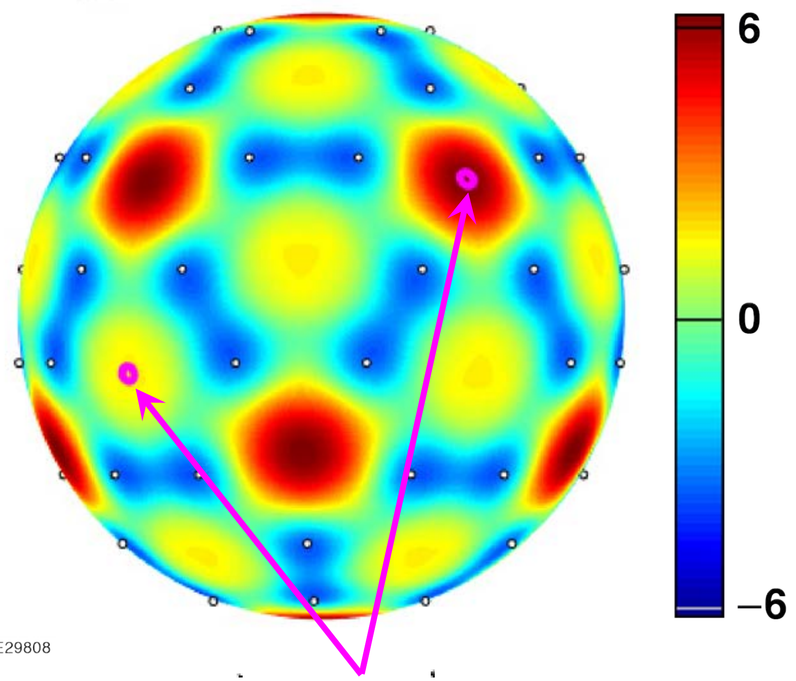
Conventional simulations predict scattered light has a larger rms variation (compared to absorption) but maintains symmetry about the OMEGA beam/port pattern

Scattered energy over chamber surface $\int P_{\mathrm{scat}}(\theta, \varphi, t)\,\mathrm{d}t$



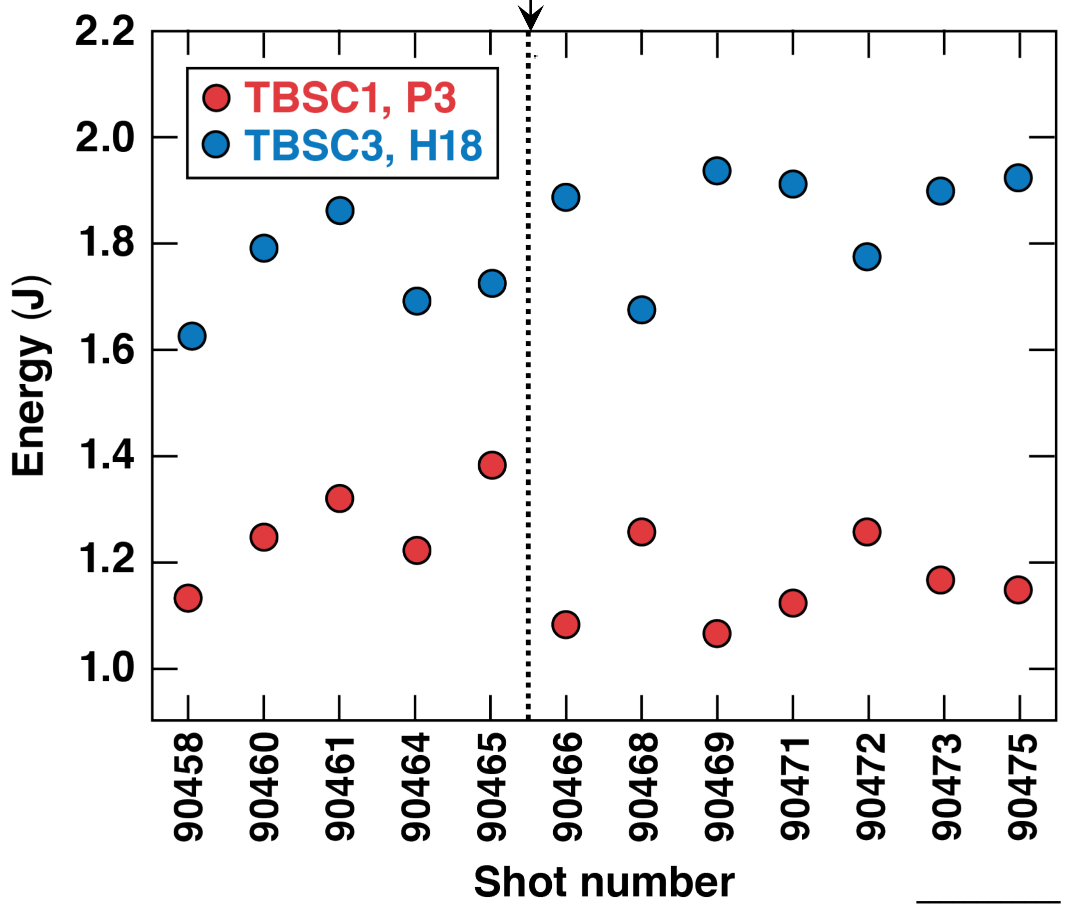
Calorimeter measurements of scattered light show much larger variation around the target chamber than predicted

Scattered energy over chamber surface
$\int P_{scat}(\theta, \varphi, t)\mathrm{d}t$



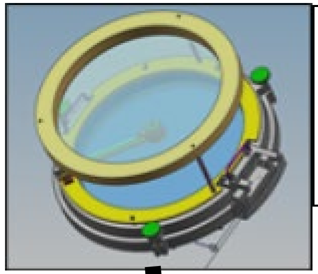
~5% difference in scattered light predicted between the two diagnostic locations

Diagnostic hardware swapped after five shots: the trend continued unchanged

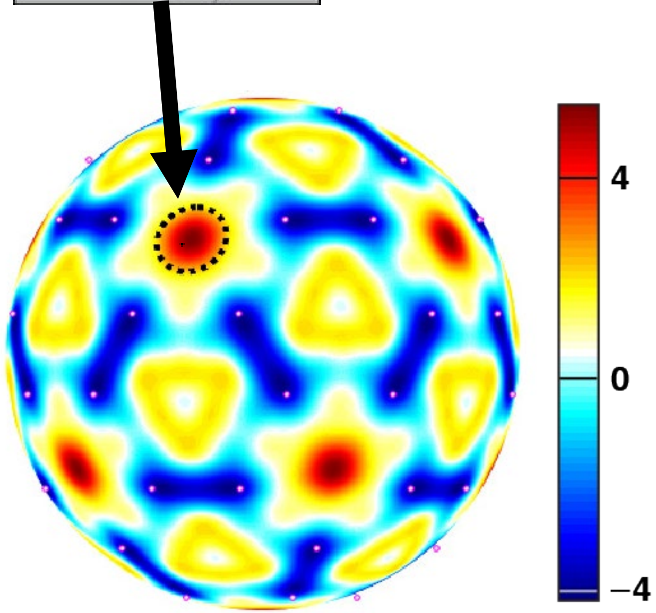


TBSC: TIM-based ScatterCal

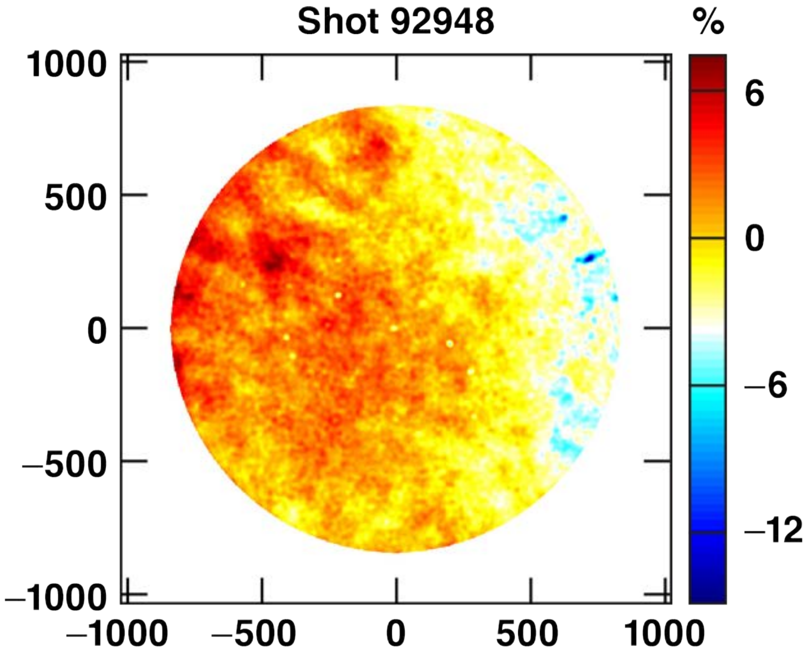
Similarly, scattered-light diffuser plate images* show significant variation over the small area of a single OMEGA port that does not conform to expected symmetry



P4 vacuum window and diffuser assembly

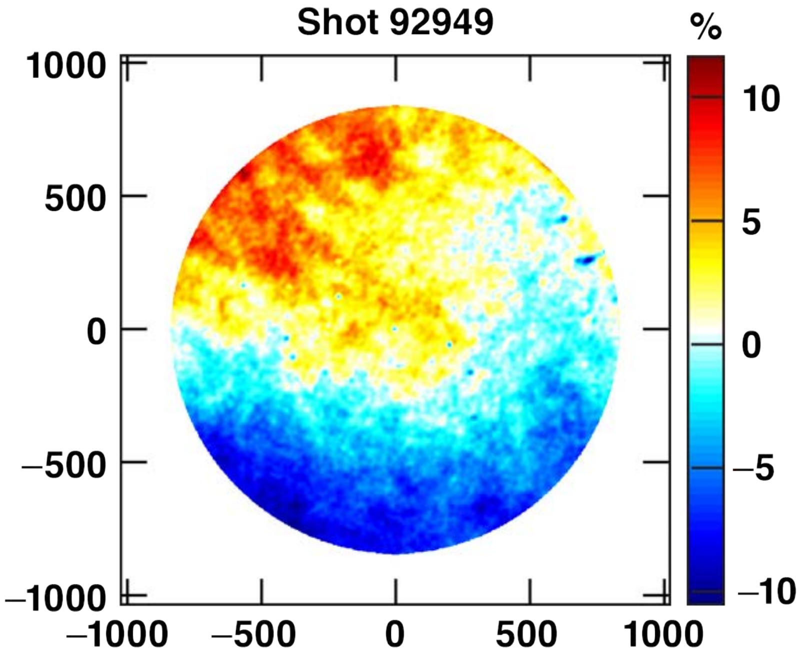


E29809



E29810

22 kJ, 1-ns-square pulse



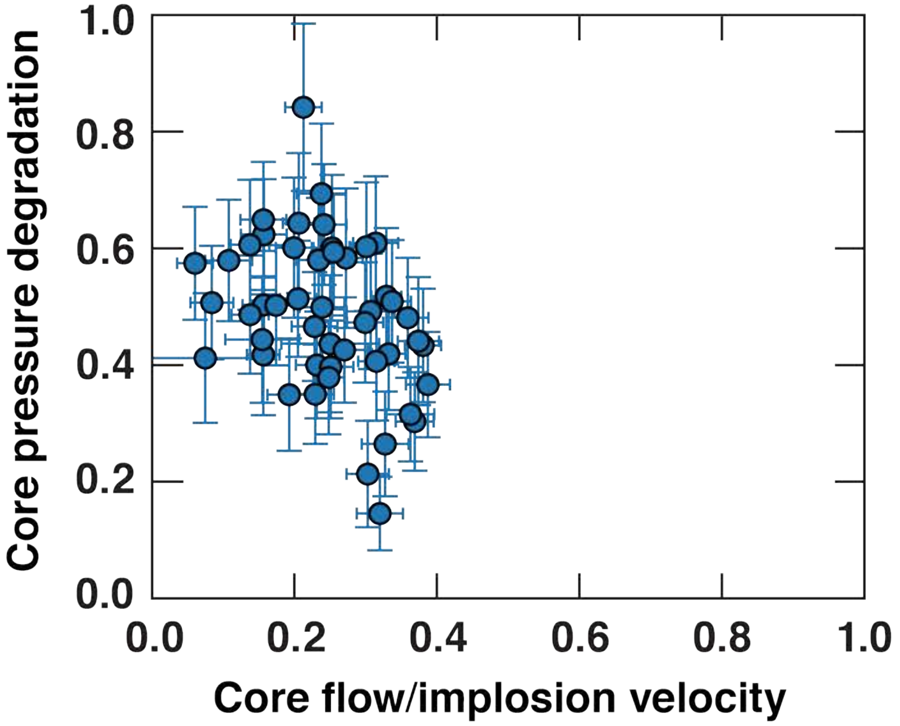
E29811

22 kJ, triple-picket shaped pulse

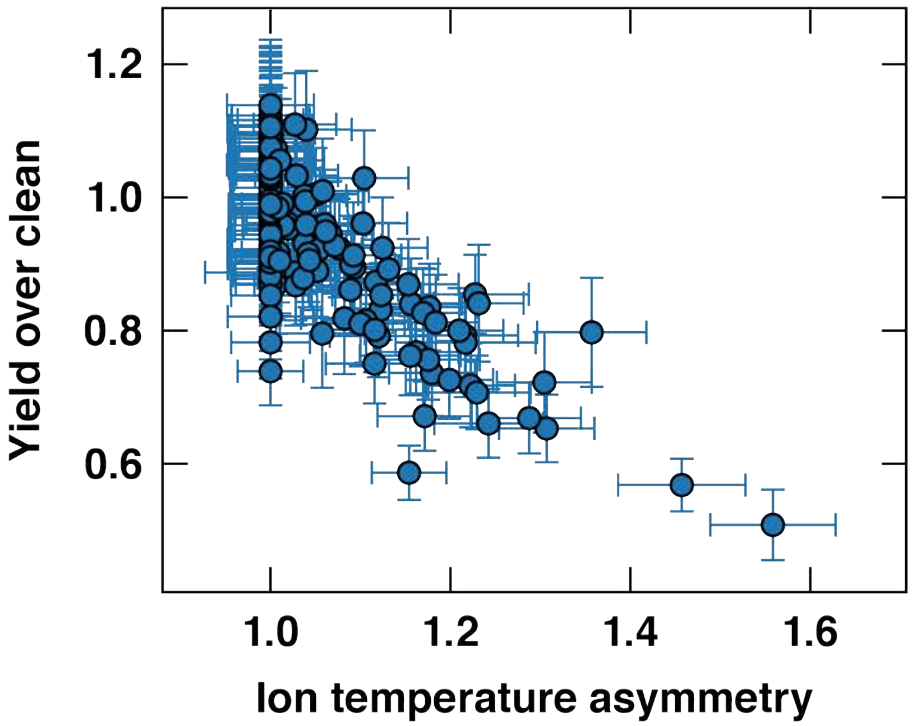
* J. Katz *et al*., Rev. Sci. Instrum. 92, 033526 (2021).

A growing body of evidence suggests OMEGA implosions are more asymmetric than predictions

Significant core flow*



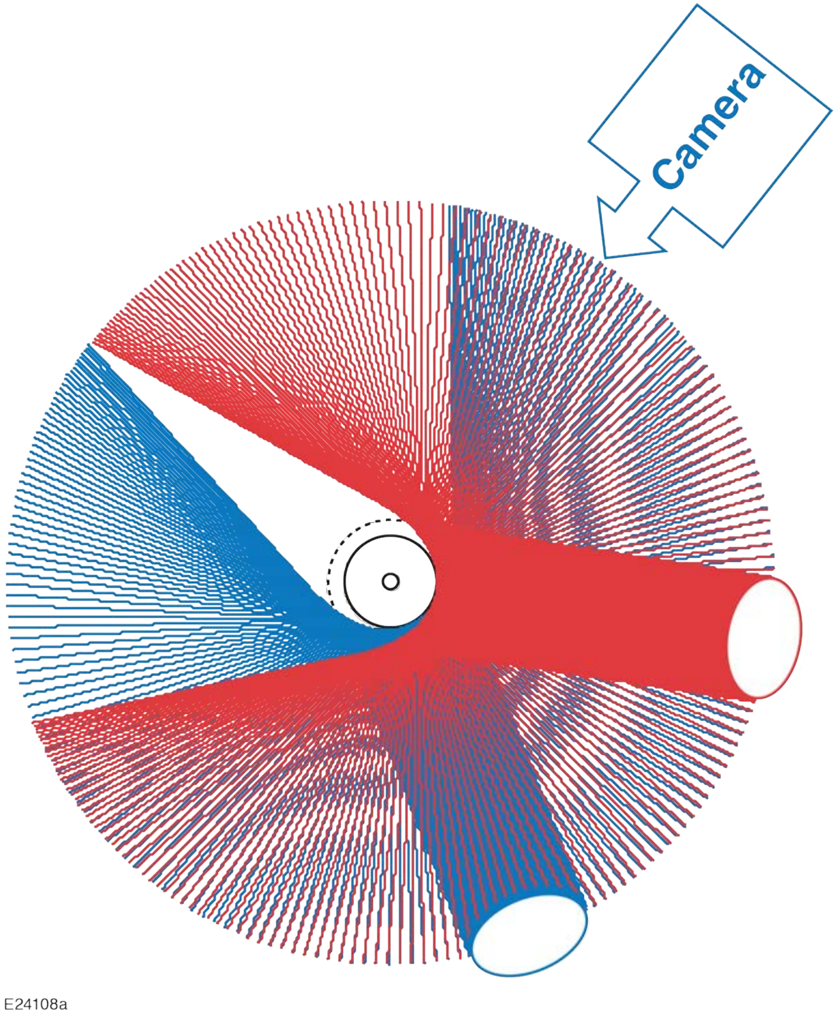
Ion temperature asymmetry**



TC15691

* O. M. Mannion *et al.*, Phys. Plasmas 28, 042701 (2021).
** A. Lees *et al.*, Phys. Rev. Lett. 127, 105001 (2021).

The 3ω gated optical imager (3ωGOI) scattered-light instrument was developed to better diagnose the asymmetry of light scattered from an implosion*



* D. H. Edgell *et al*., Rev. Sci. Instrum. 89, 10E101 (2018);
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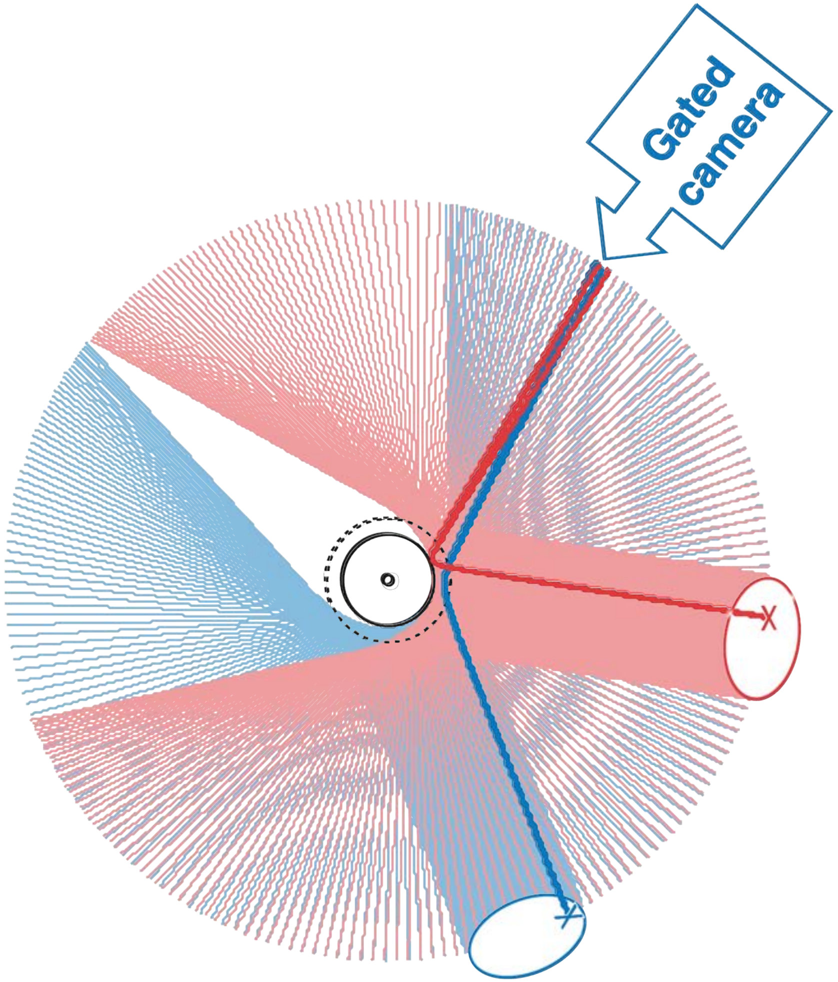

E24108b

E24108c

* D. H. Edgell *et al.*, Rev. Sci. Instrum. 89, 10E101 (2018);
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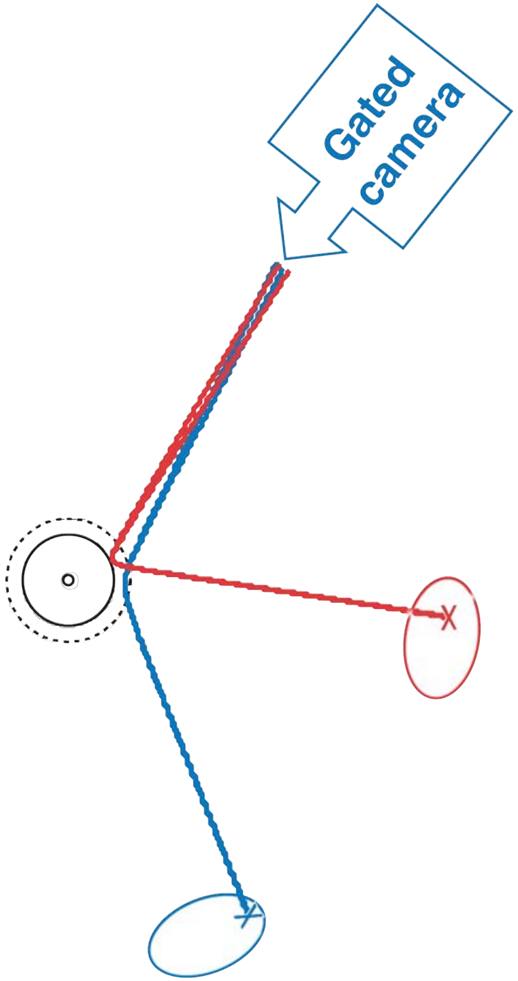

E24108c

* D. H. Edgell *et al*., Rev. Sci. Instrum. 89, 10E101 (2018);
D. H. Edgell *et al*., Rev. Sci. Instrum. 92, 043525 (2021).

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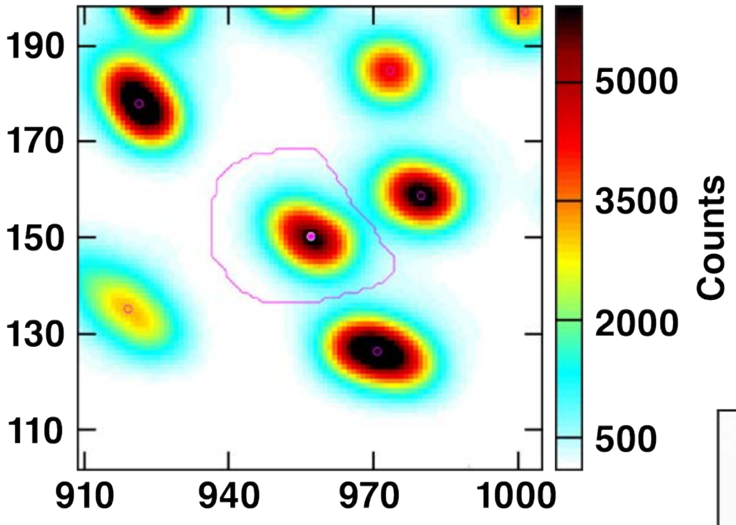
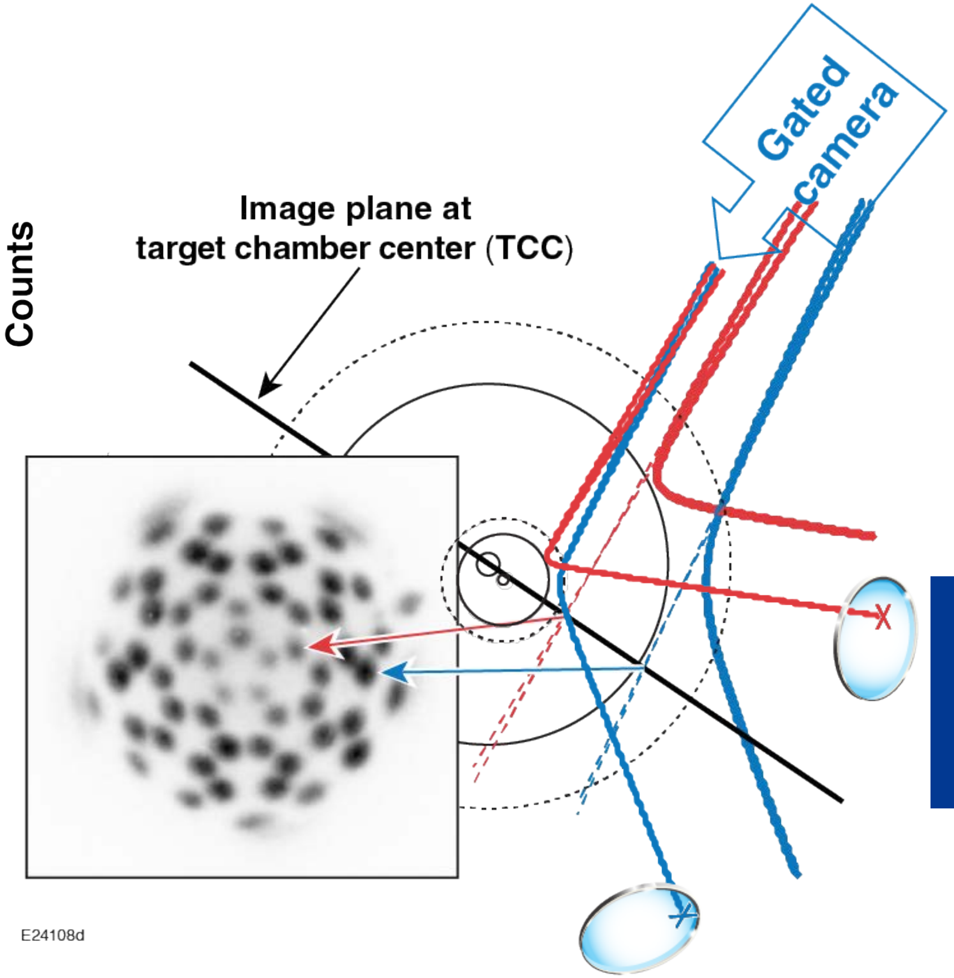


E29817



E24108d

E24108c

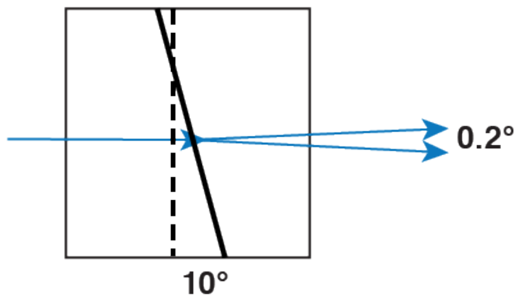
Summing the counts in the region of interest (ROI) around each beamlet allows us to quantify the intensity of light in each beamlet.

* D. H. Edgell *et al.*, Rev. Sci. Instrum. 89, 10E101 (2018);
D. H. Edgell *et al.*, Rev. Sci. Instrum. 92, 043525 (2021).

A Wollaston prism in the 3ωGOI splits the collected light into two orthogonally polarized sub-images recorded simultaneously with a 200-ps gate

Wollaston prism

Separates *s* and *p* polarization

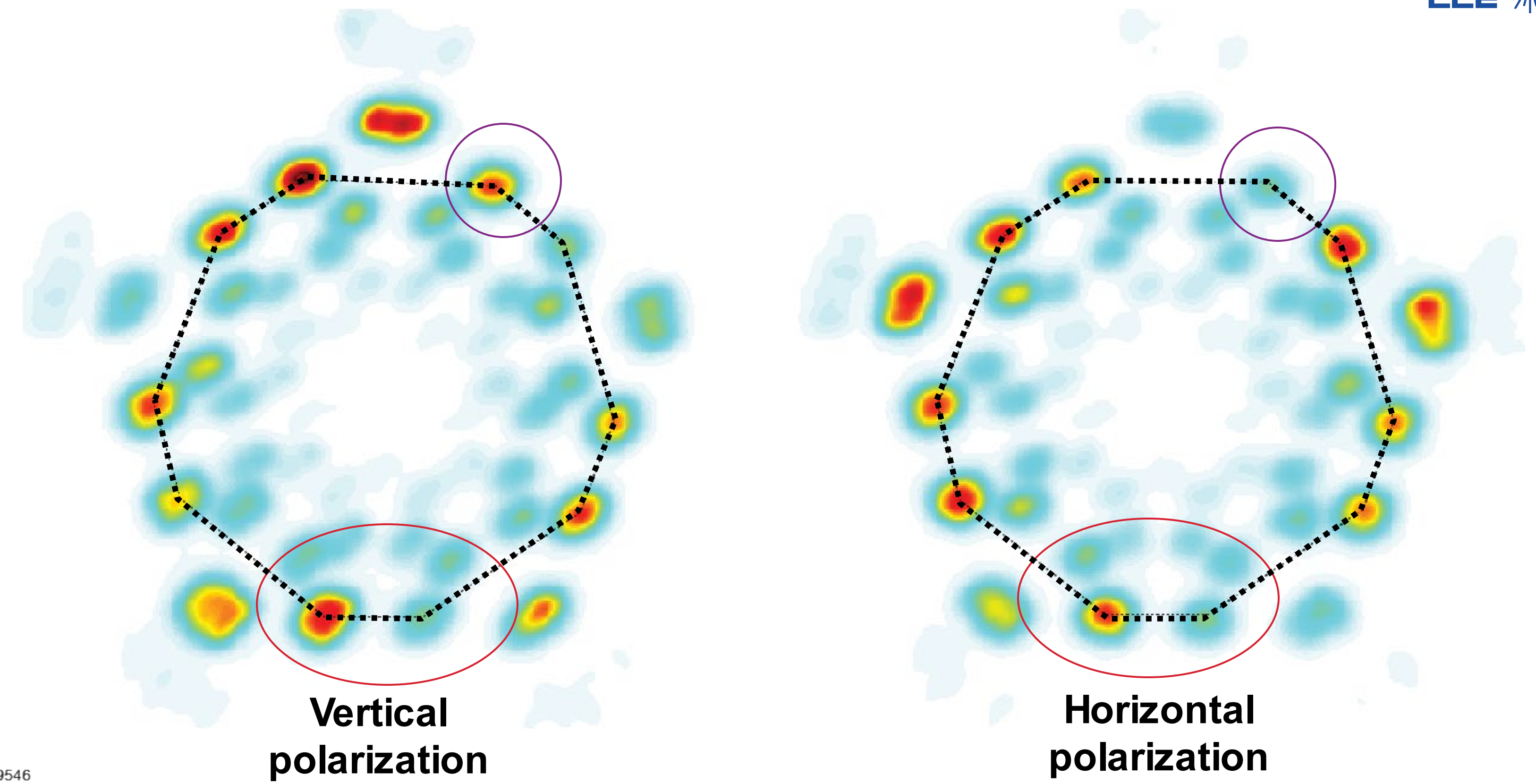


Polarization separation sets Wollaston cut angle at 10±1° (for 0.2° horizontal separation)

E29823

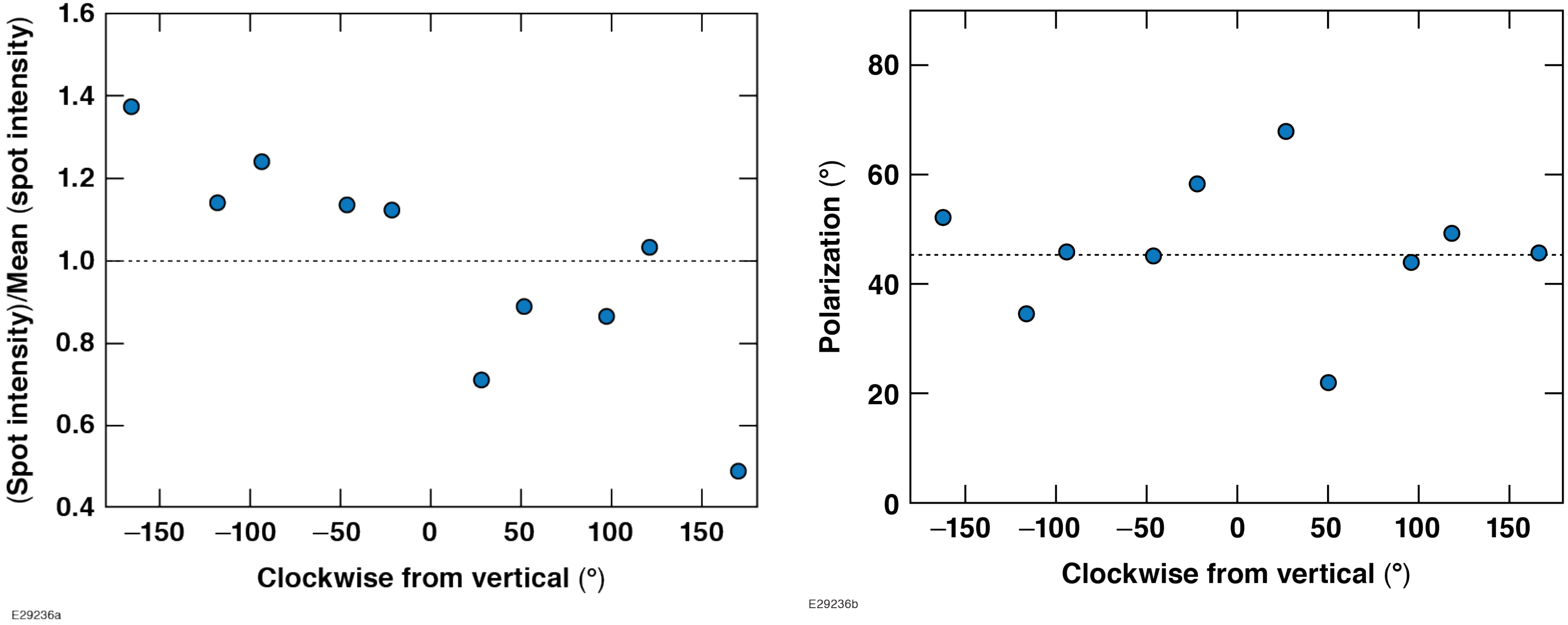
$I_b = H_\mathrm{b} + V_\mathrm{b}$, and

$P_b = \tan^{-1}(H_\mathrm{b} / V_\mathrm{b})$



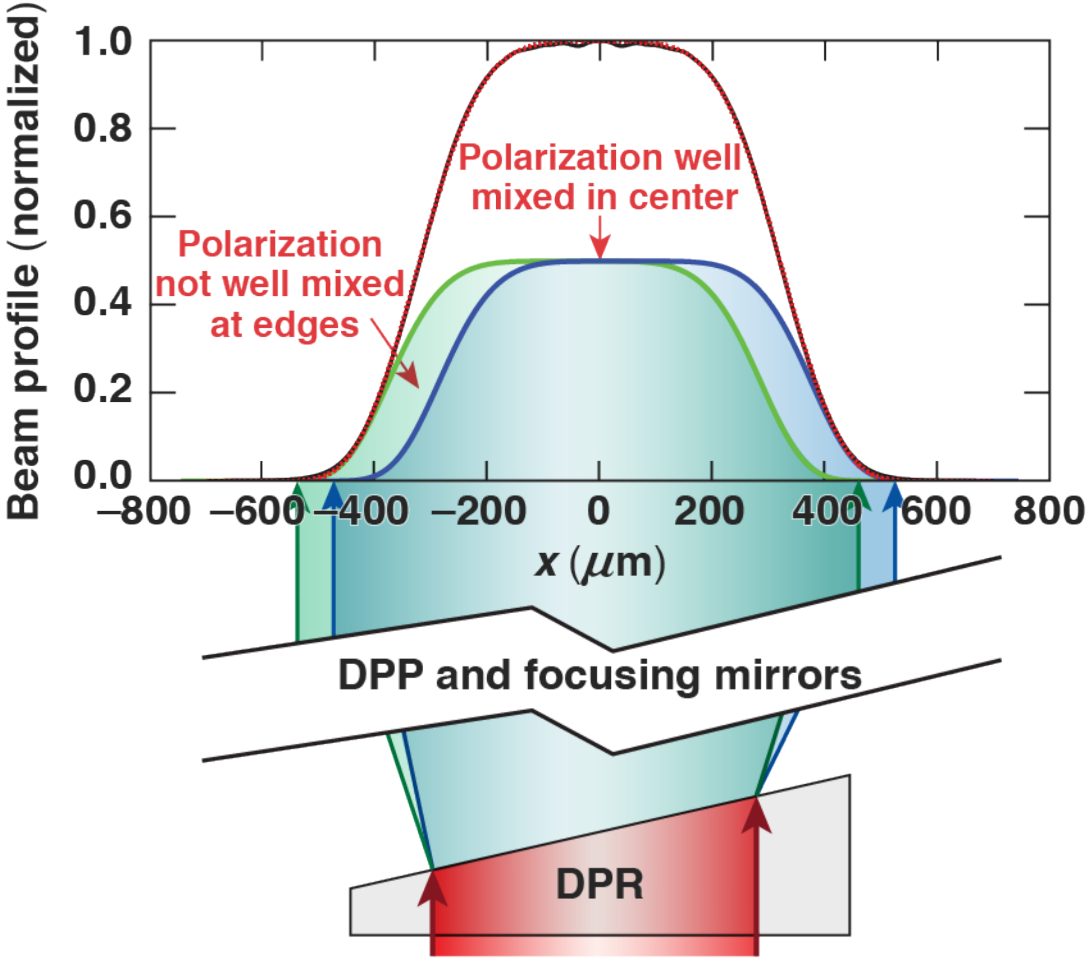
We are now able to quantify the intensity and polarization of each beamlet over a narrow window of time.

Significant variation in intensity and polarization was observed within a ring of beamlets



Such variation was not expected based on conventional CBET modeling assuming perfectly mixed polarizations.

OMEGA's polarization smoothing scheme leads to strongly polarized regions

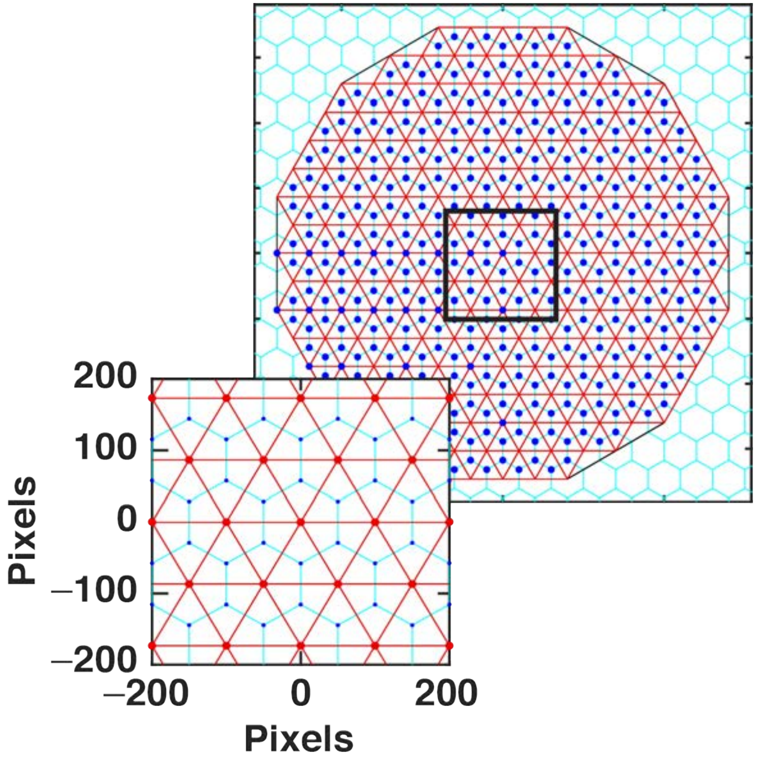


E29545

- The orthogonal polarizations are separated by 90 μm at the target plane
- The assumption of equally mixed polarizations in each beam is invalid
- CBET modeling must follow each polarization component independently

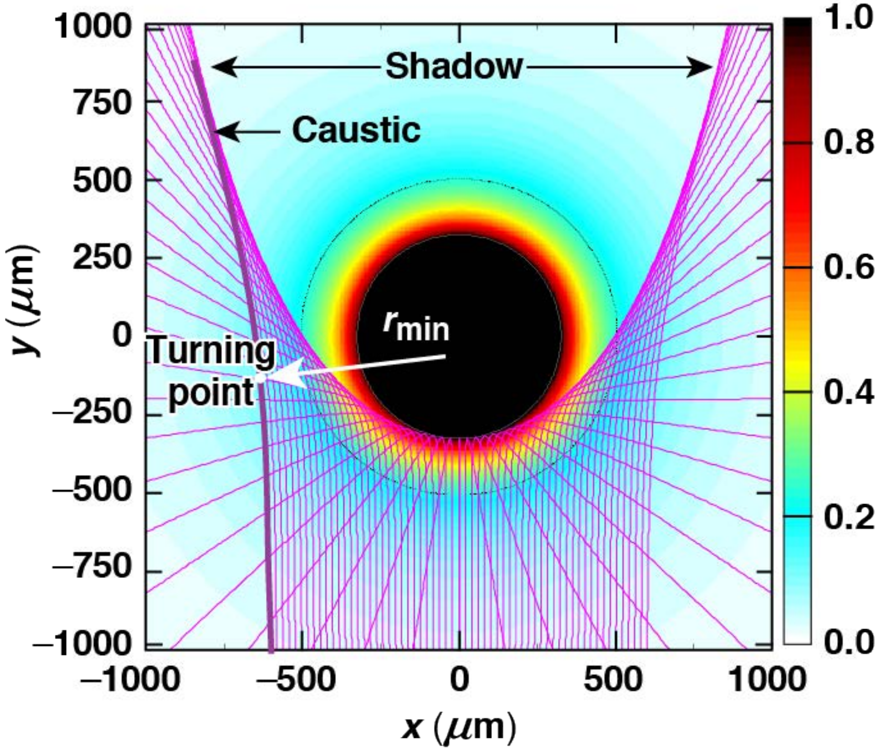
Predictions are produced by a 3-D kinetic CBET model* in a geometric optics ray-based postprocessor using the coronal plasma taken from hydrodynamic code

Each beam is divided into many beamlets

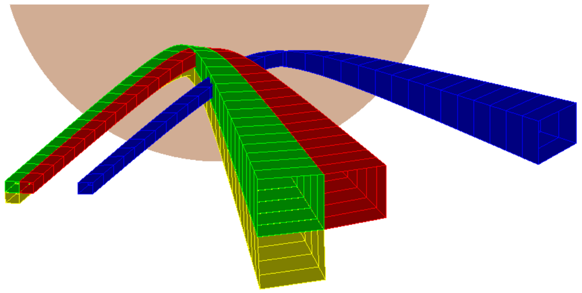


E29845

Paths of beamlets through coronal plasma determined with ray tracing



Crossings and CBET coupling coefficients calculated between all beamlets

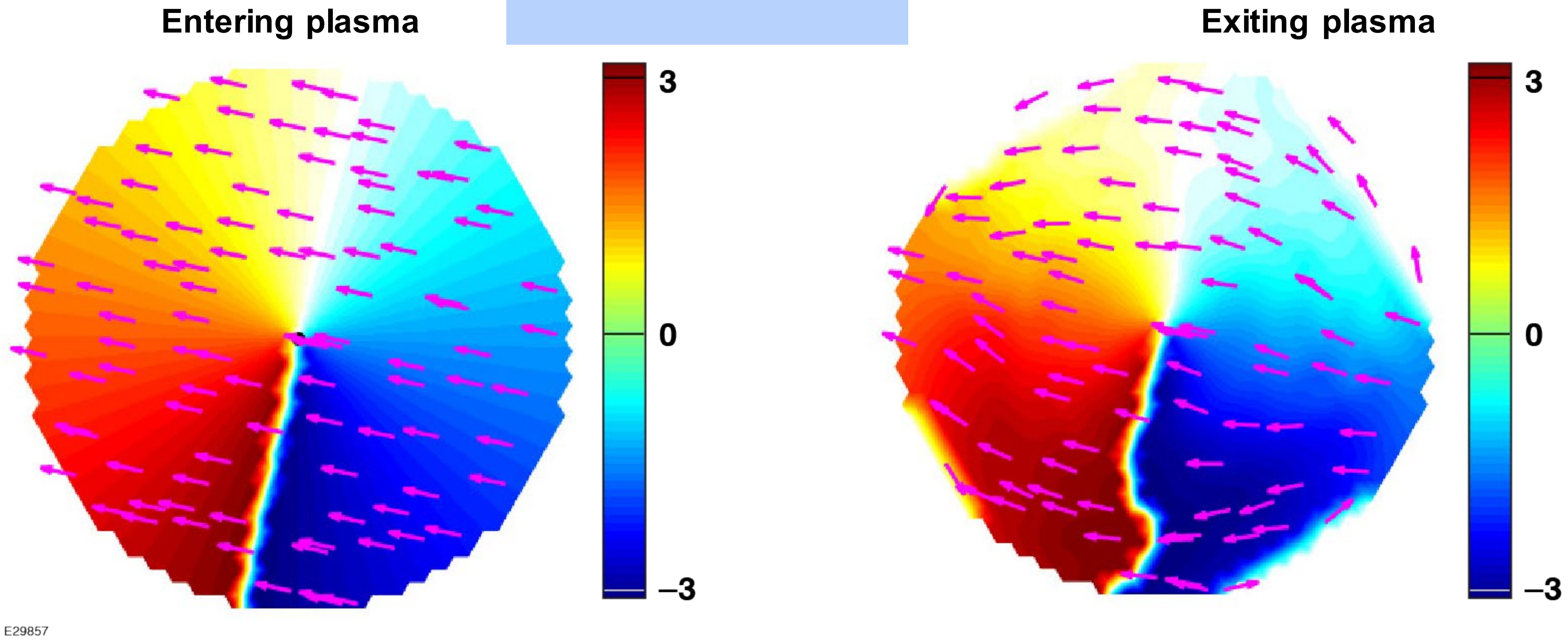


$$\omega_{IAW} = \omega_1 - \omega_2$$

$$\vec{k}_{IAW} = \vec{k}_1 - \vec{k}_2$$

* D. H. Edgell *et al.*, Phys. Plasmas 24, 062706 (2017).

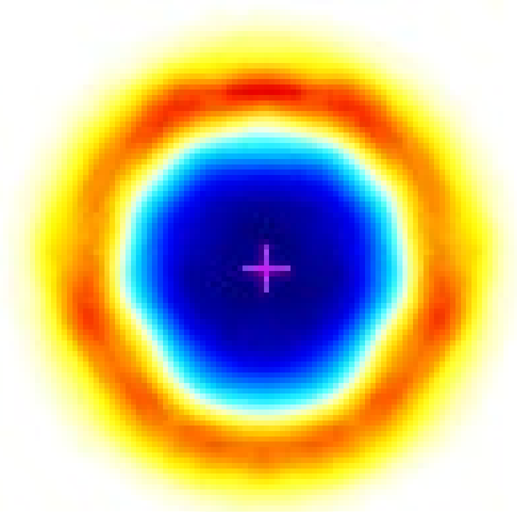
The 3D model tracks the polarization of each beamlet and calculates its rotation due to CBET



- *s* and *p* polarization components tracked through coronal plasma and rotated by CBET with other beams
- Arrows in exit plot use the *s* and *p* components after traversing the plasma on the same polarization unit vectors as in initial plot

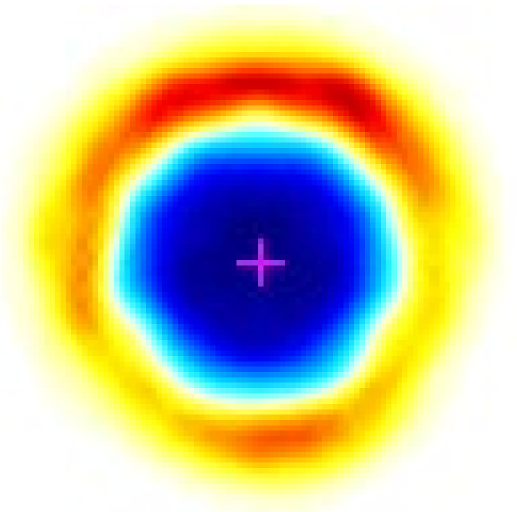
Three-dimensional modeling of DPR polarizations splits and offsets with correct sub-beam intensity profiles predicts a CBET-induced asymmetry that is different for each beam

60 beams split into two orthogonal polarizations each = 120 beams in model



$$\sum_s \mathrm{d}E_{\mathrm{CBET}}$$

Sum of energy exchange along beamlet paths through plasma (both orthogonal polarization sub-beams added together to get a single full beam)



No offset, full SG5 beam profiles

62% absorption

90-μm offset, "no DPR" beam profiles

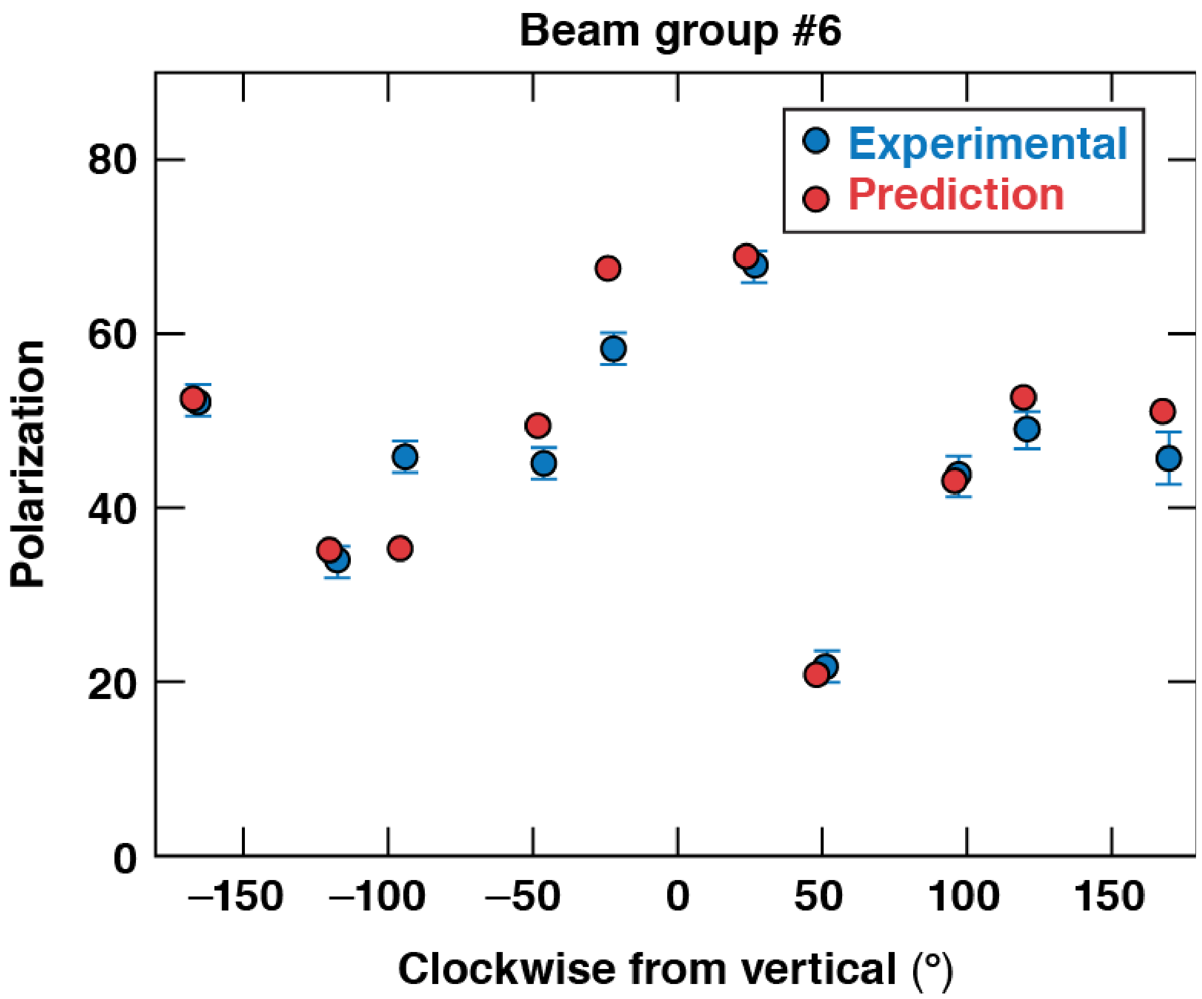
61% overall absorption

Results identical to 60-beams modeling using the simple DPR factor*

$$\Theta = \frac{1}{4}\left(1 + \cos^2\theta_k\right)$$

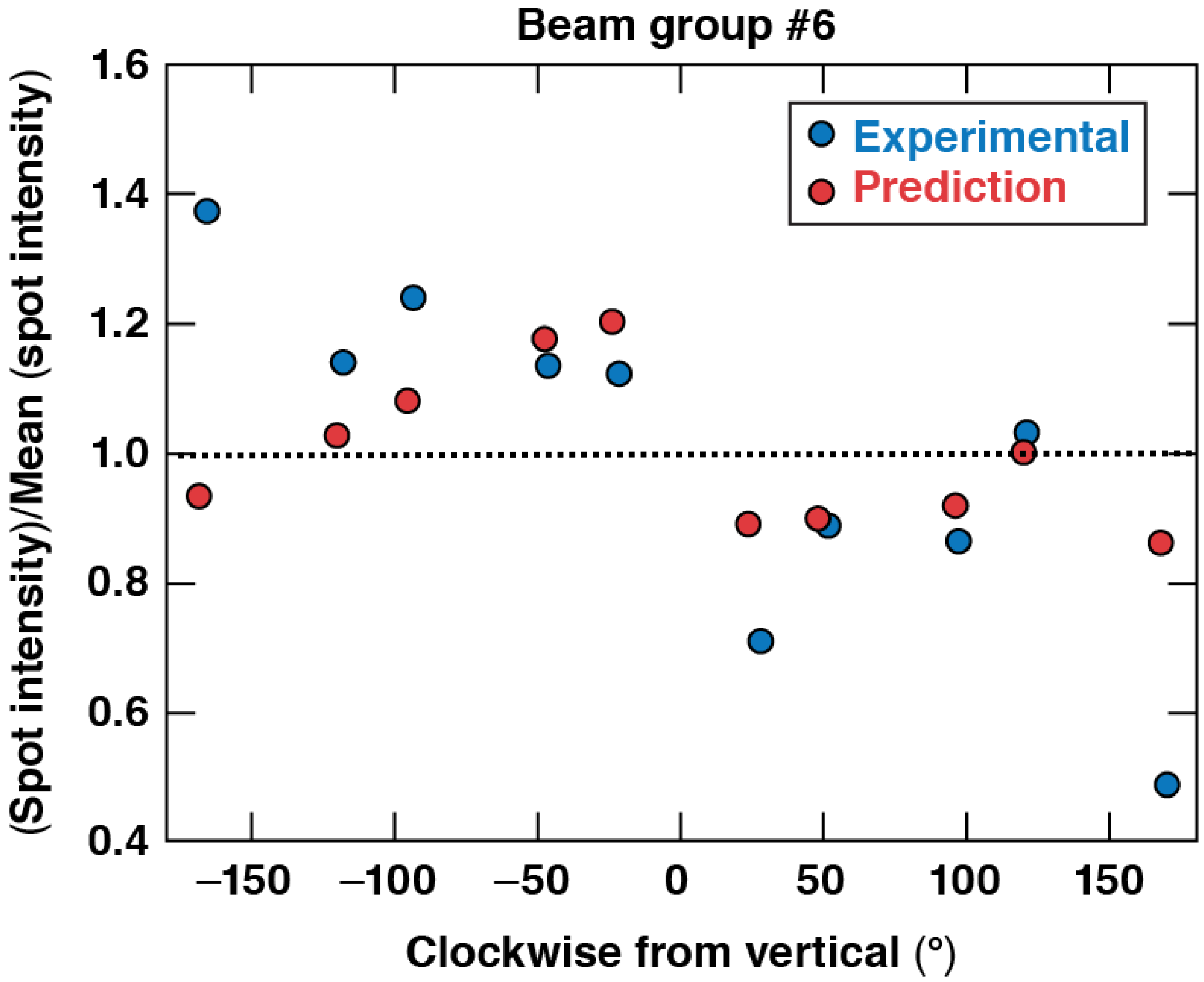
* P. Michel *et al.*, Phys. Plasmas 20, 056308 (2013).

The 3ωGOI predicted beamlet spot polarizations using 120 split and offset DPR beams are now very similar to the measurements



- Strong evidence that the DPR offset is the source of the scattered-light polarization

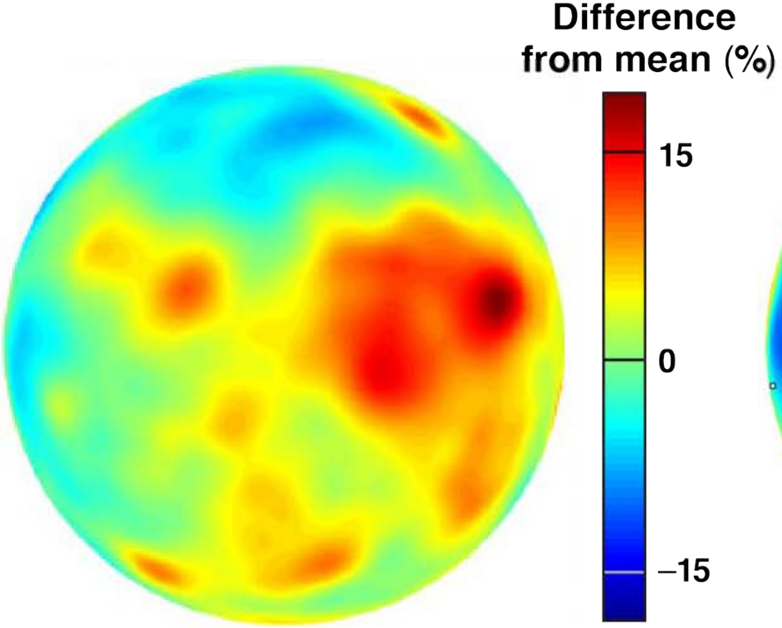
The 3ωGOI predicted beamlet spot intensities using 120 split and offset DPR beams are also similar to the measurements



- A couple spot intensities are still significantly different
- May be due to
  - differences in the individual beam profiles
  - pointing errors in the beams

The full polarization CBET modeling predicts very nonuniform scattered light and absorption distributions

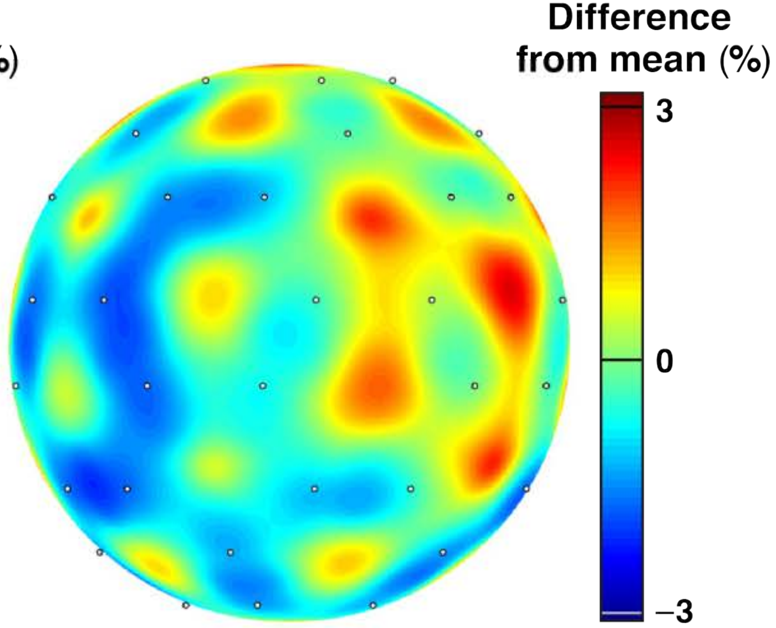
Scattered energy over chamber surface $\int P_{\mathrm{scat}}(\theta,\varphi,t)\mathrm{d}t$



E29856a

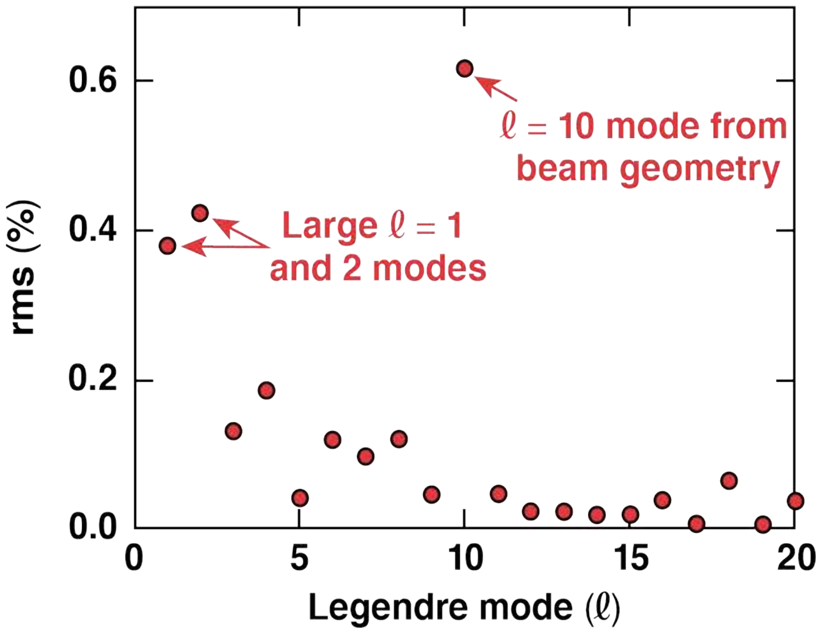
±5.42% rms
32.6% P-V

Absorbed energy over target surface $\int P_{\mathrm{abs}}(\theta,\varphi,r,t)\mathrm{d}r\mathrm{d}t$

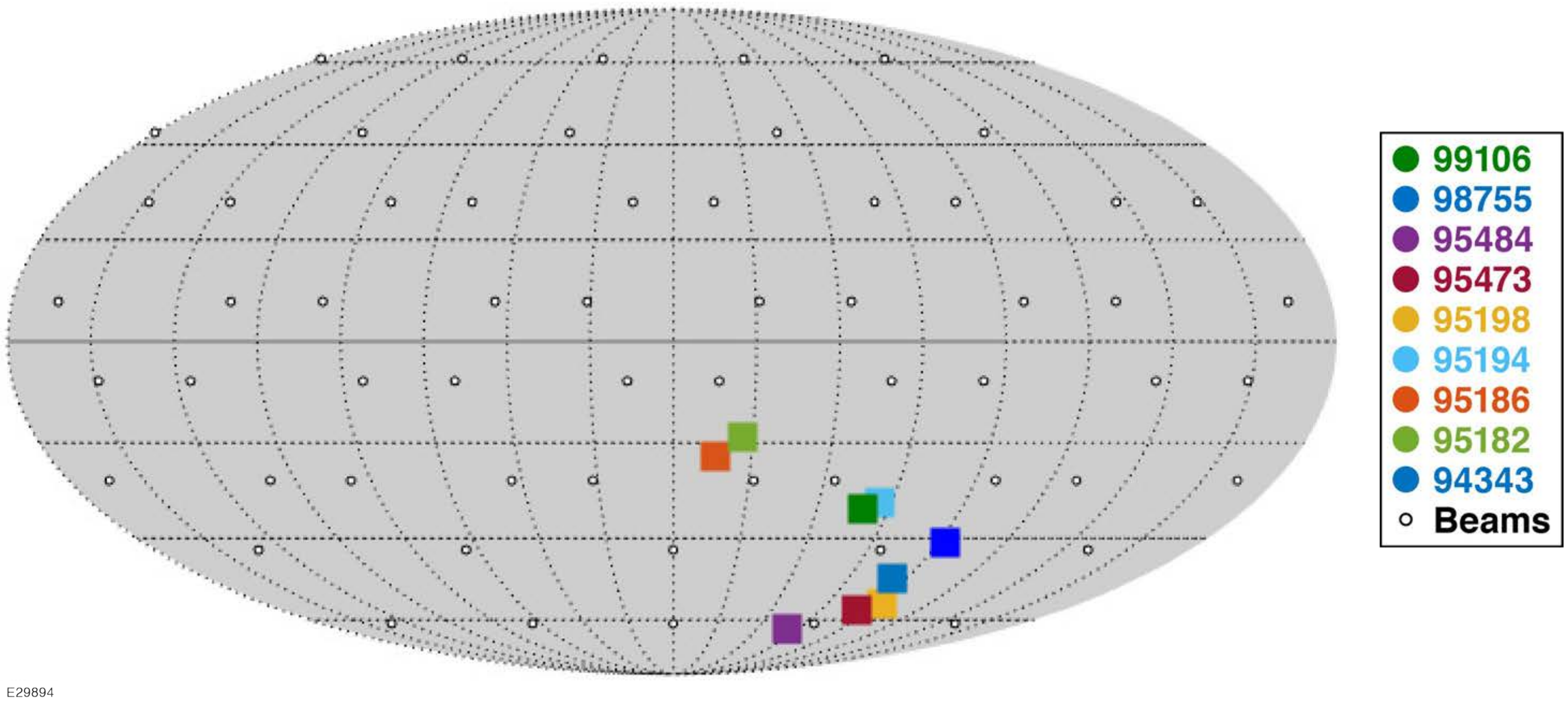


± 0.90% rms
5.3% P-V

Spherical harmonic decomposition



The full polarization CBET modeling always predicts the location of the absorbed energy mode 1 maximum to be opposite the OMEGA core flow trend



- **Squares: core flow direction**

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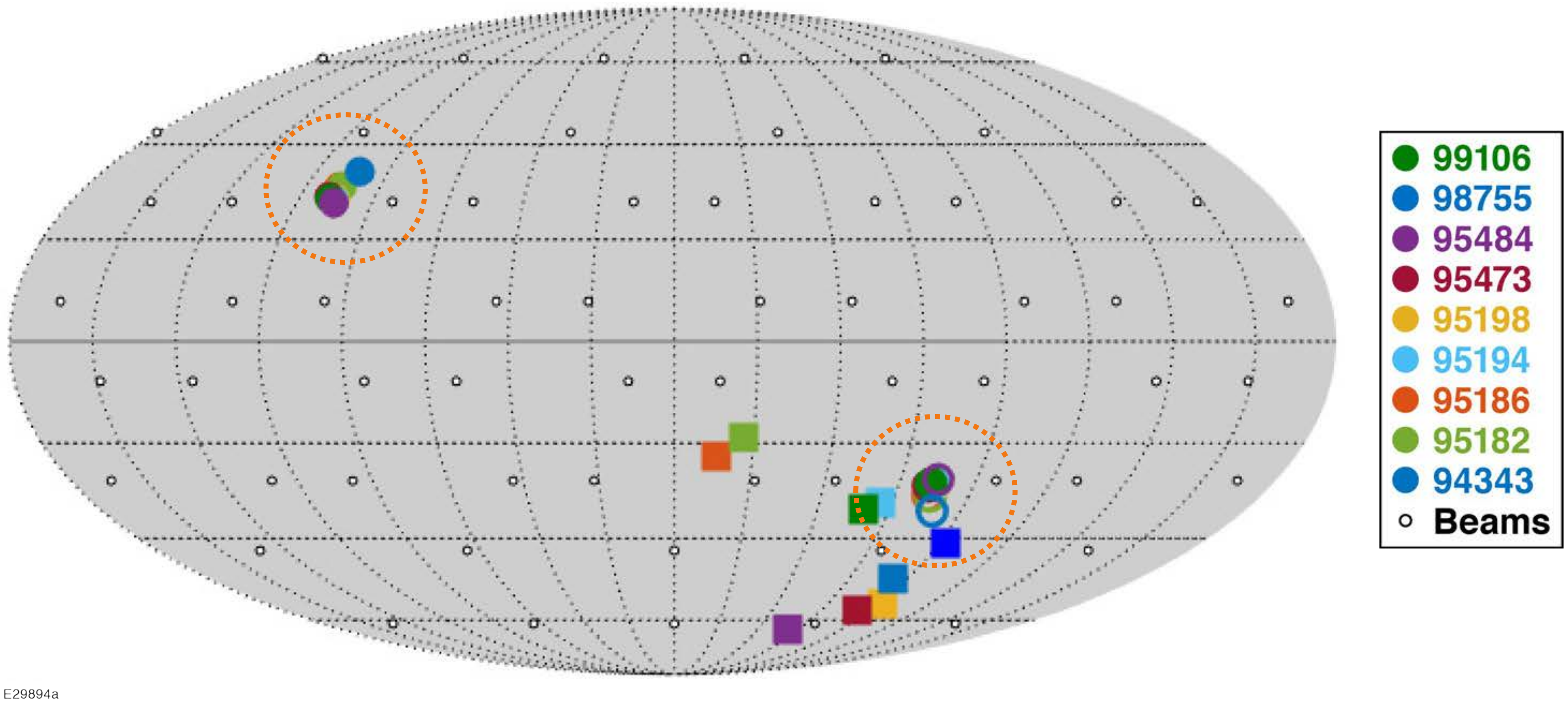
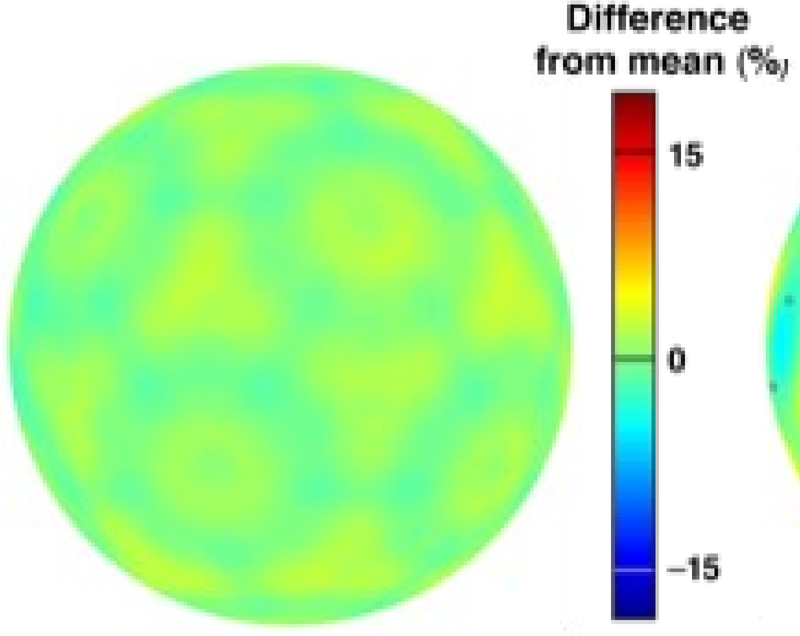


- **Squares: core flow direction**
- **Circles: absorption mode 1**

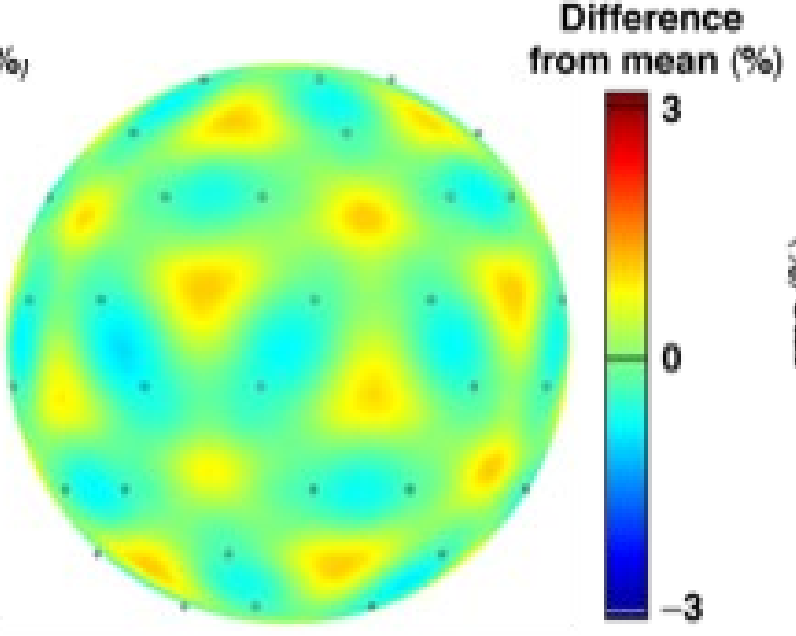
Modeling predicts that reducing the DPR polarization offset on target to 10 μm will reduce nonuniformity to acceptable levels

Scattered energy over chamber surface $\int P_{\text{scat}}(\theta, \varphi, t)\mathrm{d}t$



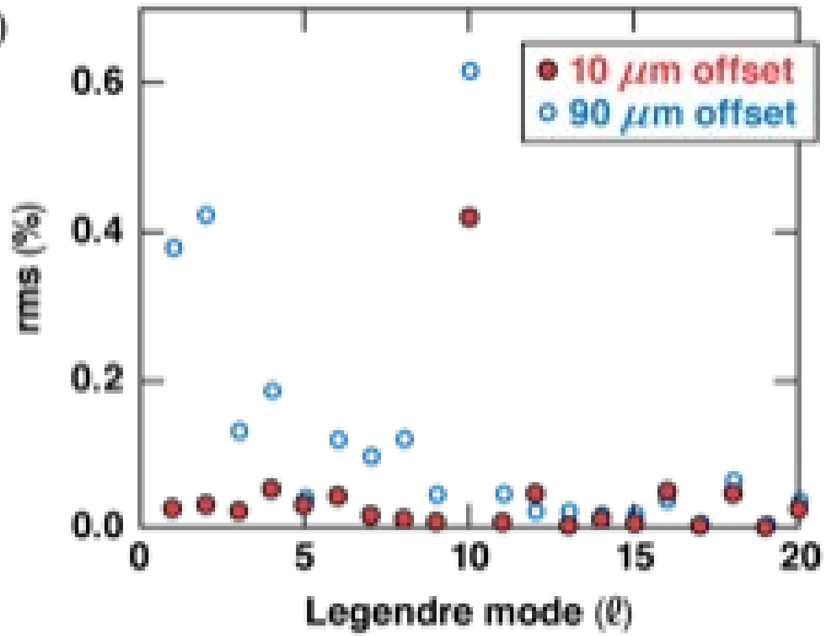
$\pm$ **0.93% rms**
5.3 % P-V

Absorbed energy over target surface $\int P_{\text{abs}}(\theta, \varphi, r, t)\mathrm{d}r\mathrm{d}t$



$\pm$ **0.44% rms**
2.2 % P-V

Spherical harmonic decomposition



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- A growing body of evidence (including hot-spot flows, ion-temperature asymmetry, and nonuniform scattered light) suggests OMEGA implosions are more asymmetric than predictions
- By measuring the intensity and polarization of light scattered from individual beams, we have identified OMEGA's polarization smoothing via distributed polarization rotators (DPR's) as one previously unrealized source of nonuniformity
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