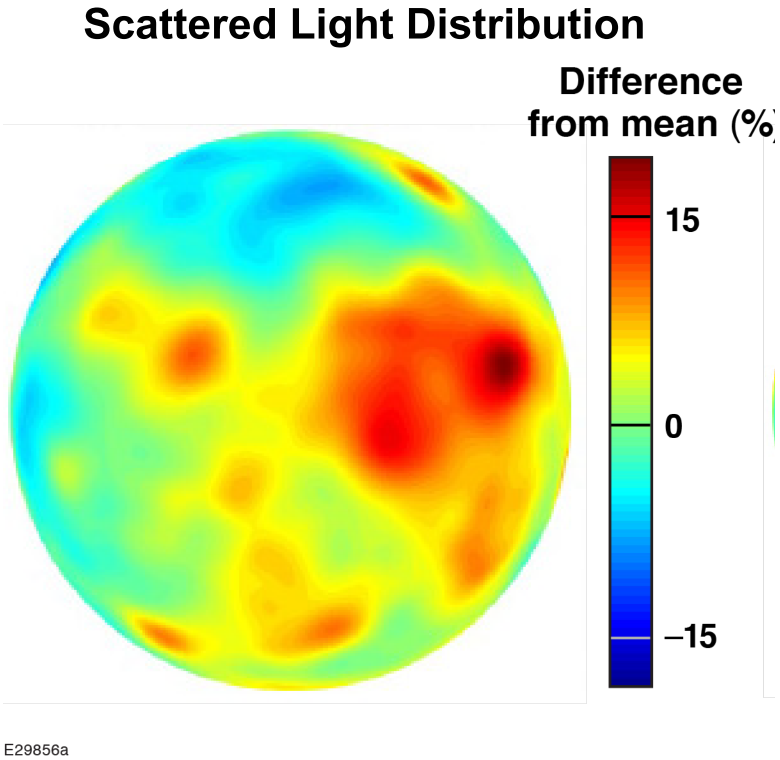
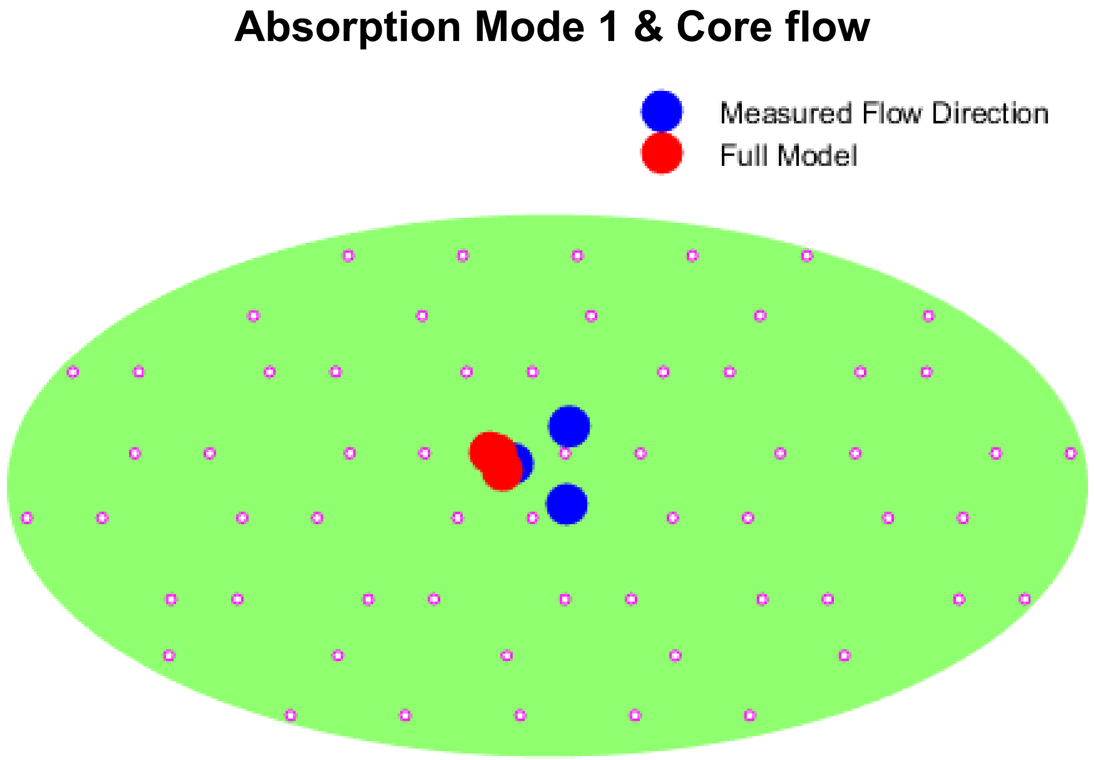
CBET–induced nonuniformity in direct-drive implosions on OMEGA





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

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Summary

Three dimensional polarization-dependent CBET plus beam balance and pointing are required to model nonuniformity in direct-drive implosions on OMEGA

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- Uniform laser energy absorption is essential for successful laser-direct-drive inertial confinement fusion but a growing body of evidence 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
- Polarization-dependent CBET along with beam energy balance, and beam pointing require three-dimensional modeling
- Laser absorption mode 1 predictions from a fully three-dimensional CBET model correlate well with the observed direction of the core flow.

Collaborators

R. Shah,[1] A. Colaïtis,[2] M. J. Guardalben,[1] A. Kalb,[1] J. Katz,[1] J. Kwiatkowski,[1]
O. M. Mannion,[3] A. Shvydky,[1] C. Stoeckl,[1] D. Turnbull,[1] and D. H. Froula[1]

[1] Laboratory for Laser Energetics, University of Rochester,
250 East River Rd., Rochester, NY 14623-1299, USA
[2] CELIA, Université de Bordeaux, France
[3] Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

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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**

Individual beams are smoothed by*

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

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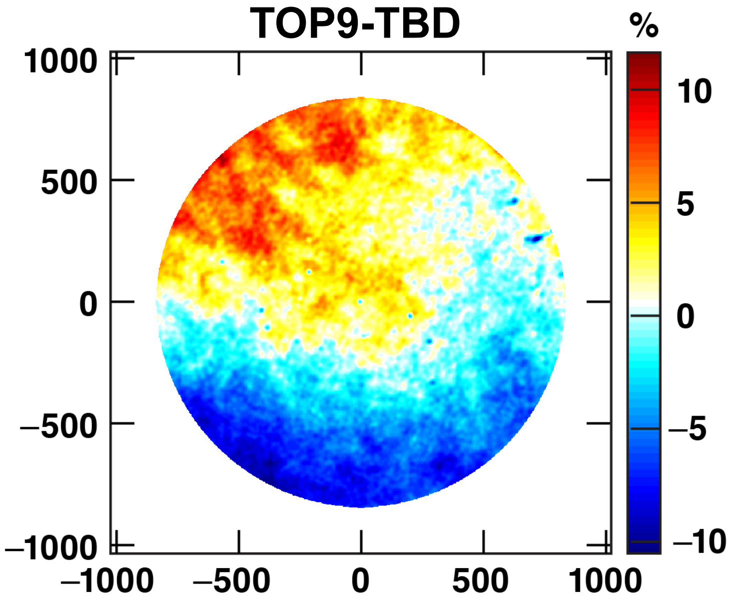
* R. S. Craxton *et al.*, Phys. Plasmas 22, 110501 (2015).
** LLE Review Quarterly Report 19, 120 (1984).
† T. R. Boehly *et al.*, J. Appl. Phys. 85, 3444 (1999).

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

Neutronics evidence:
- Significant core flow*
- Ion temperature asymmetry**

Scattered light:
- Calorimeters
- TOP9-TBD
- 3wGOI



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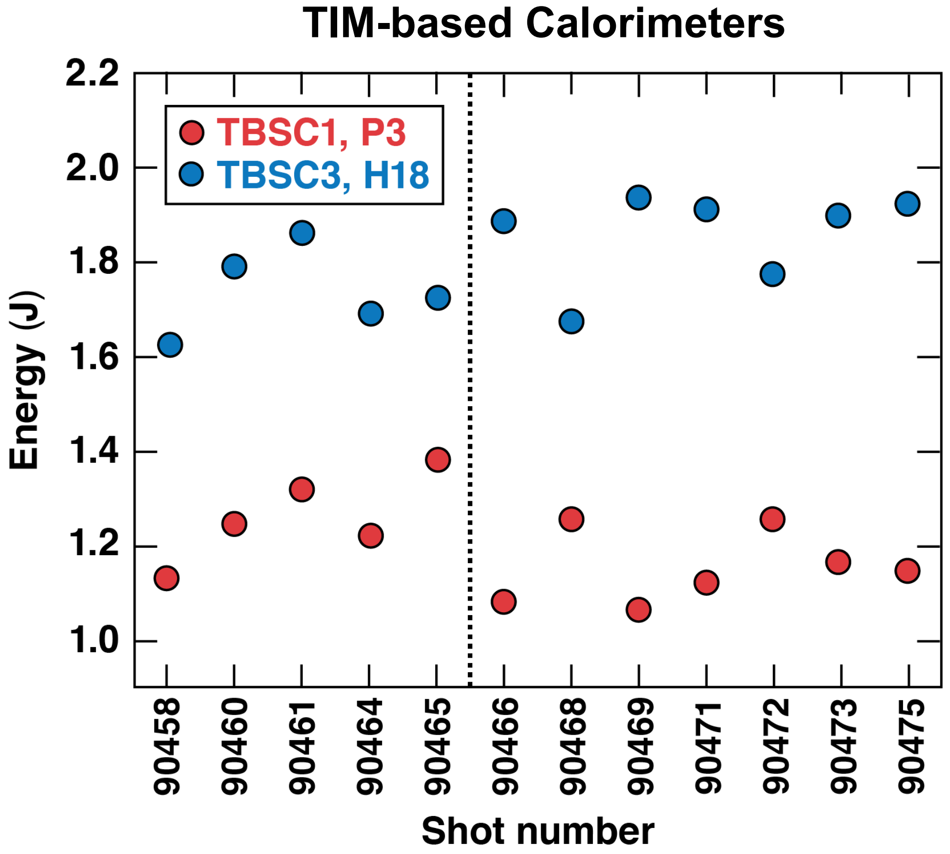
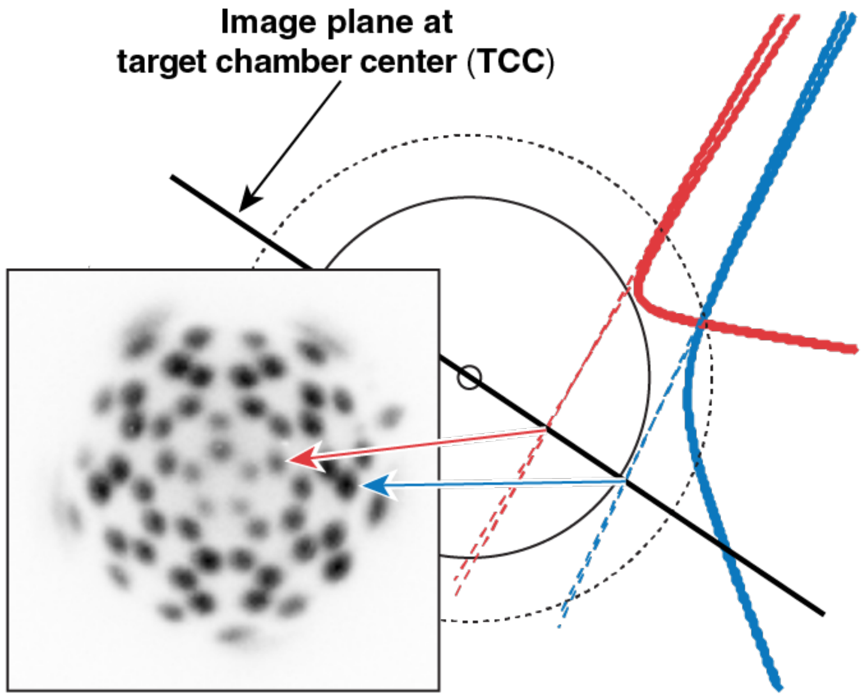


E29825

Diagnostic hardware swapped after five shots: the trend continued unchanged

* 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) was designed to study the scattered light nonuniformity in detail.



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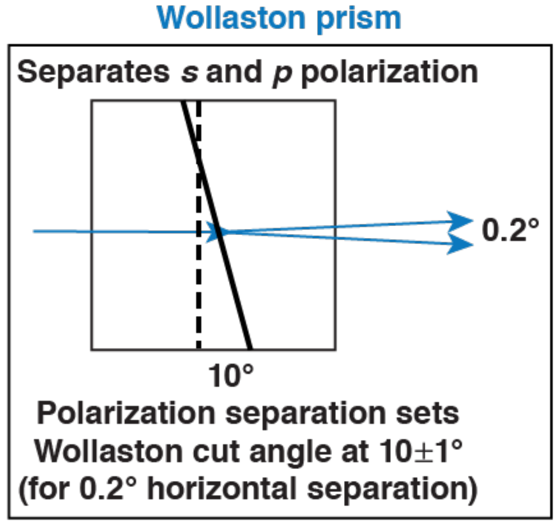

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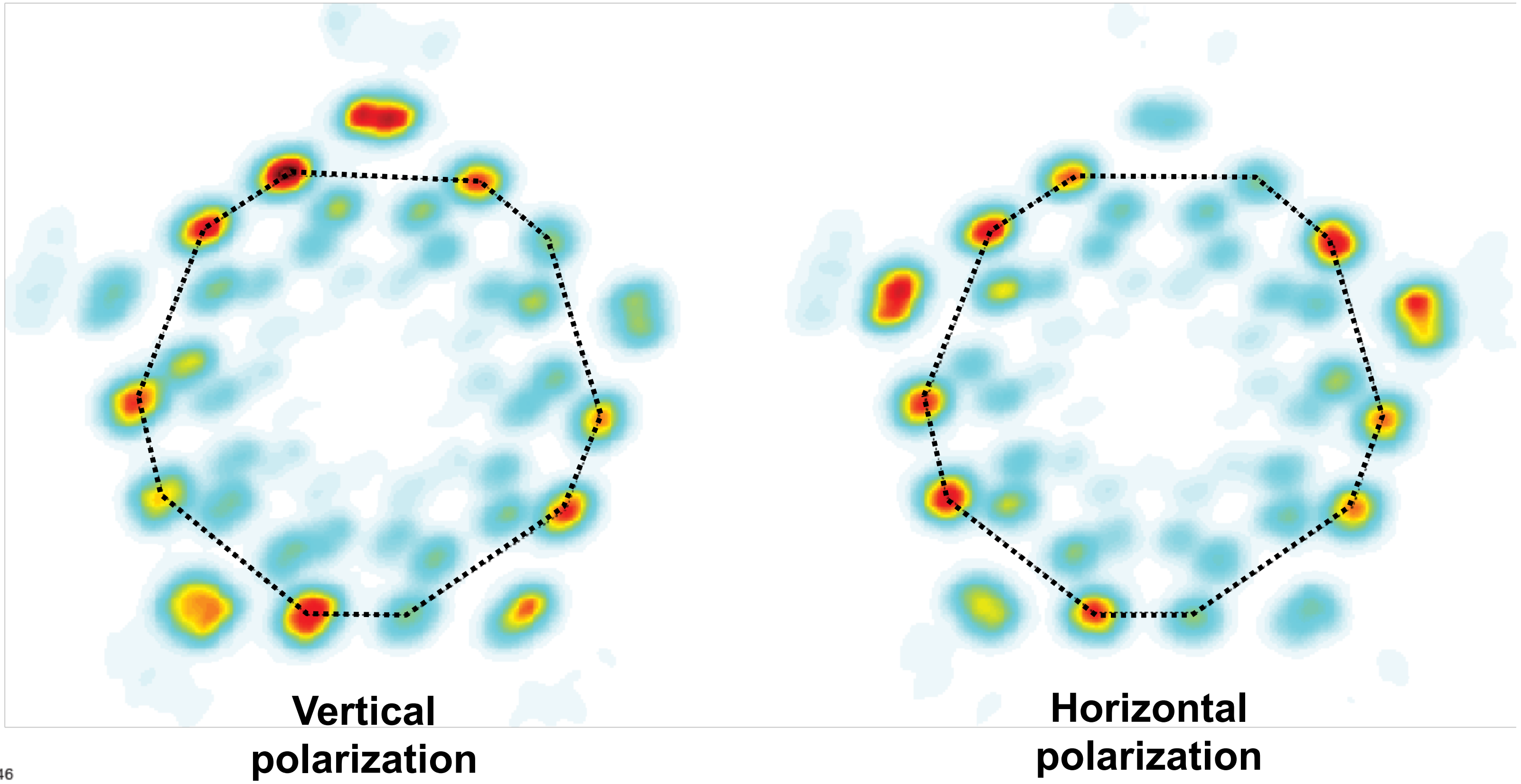
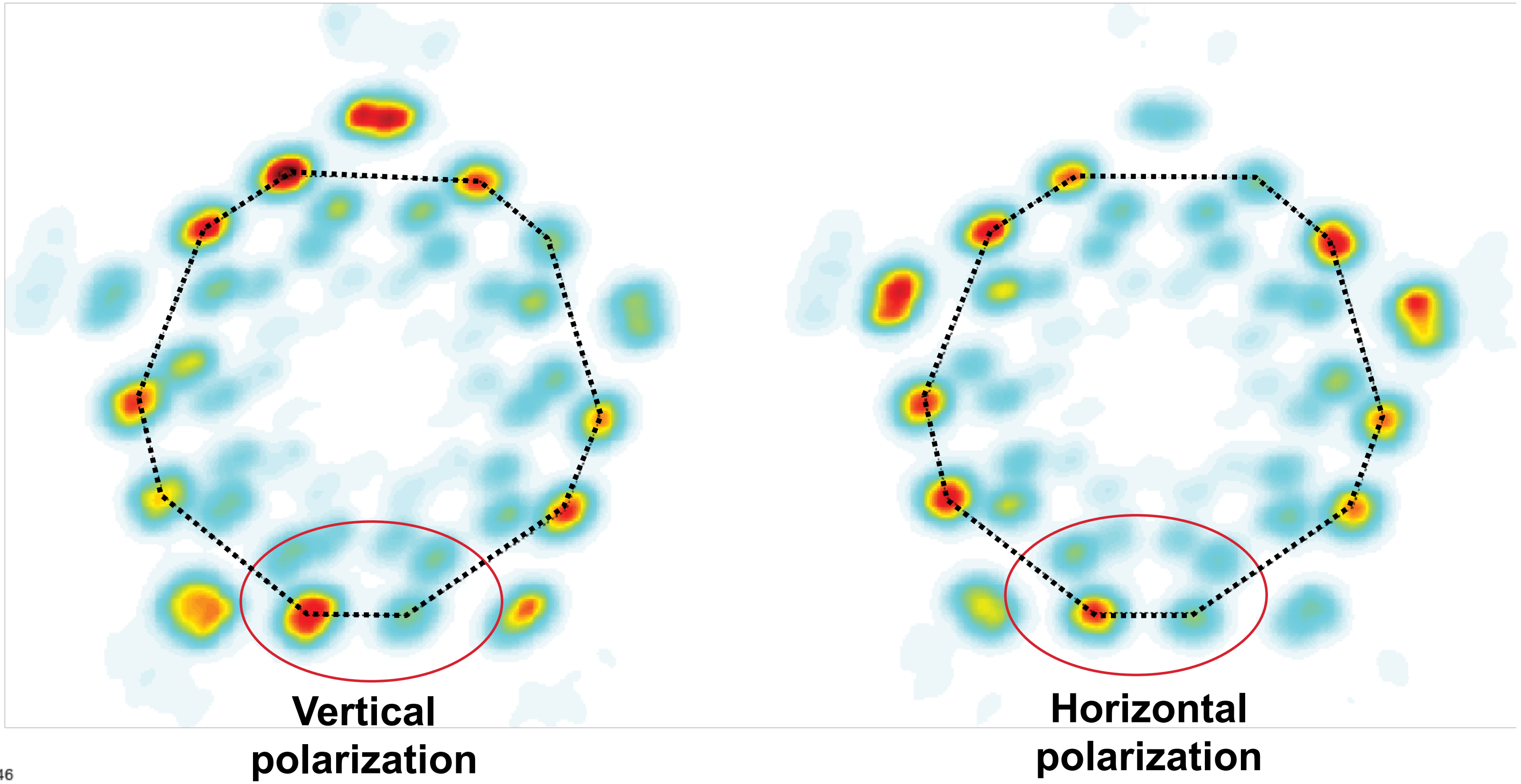
We are able to quantify the intensity and polarization of light from individual beams over a narrow window of time.

The 3ω Gated-Optical Imager (3ωGOI) showed that the scattered light was not only non-uniform but highly polarized.



E29546

The 3ω Gated-Optical Imager (3ωGOI) showed that the scattered light was not only non-uniform but highly polarized.



E29546

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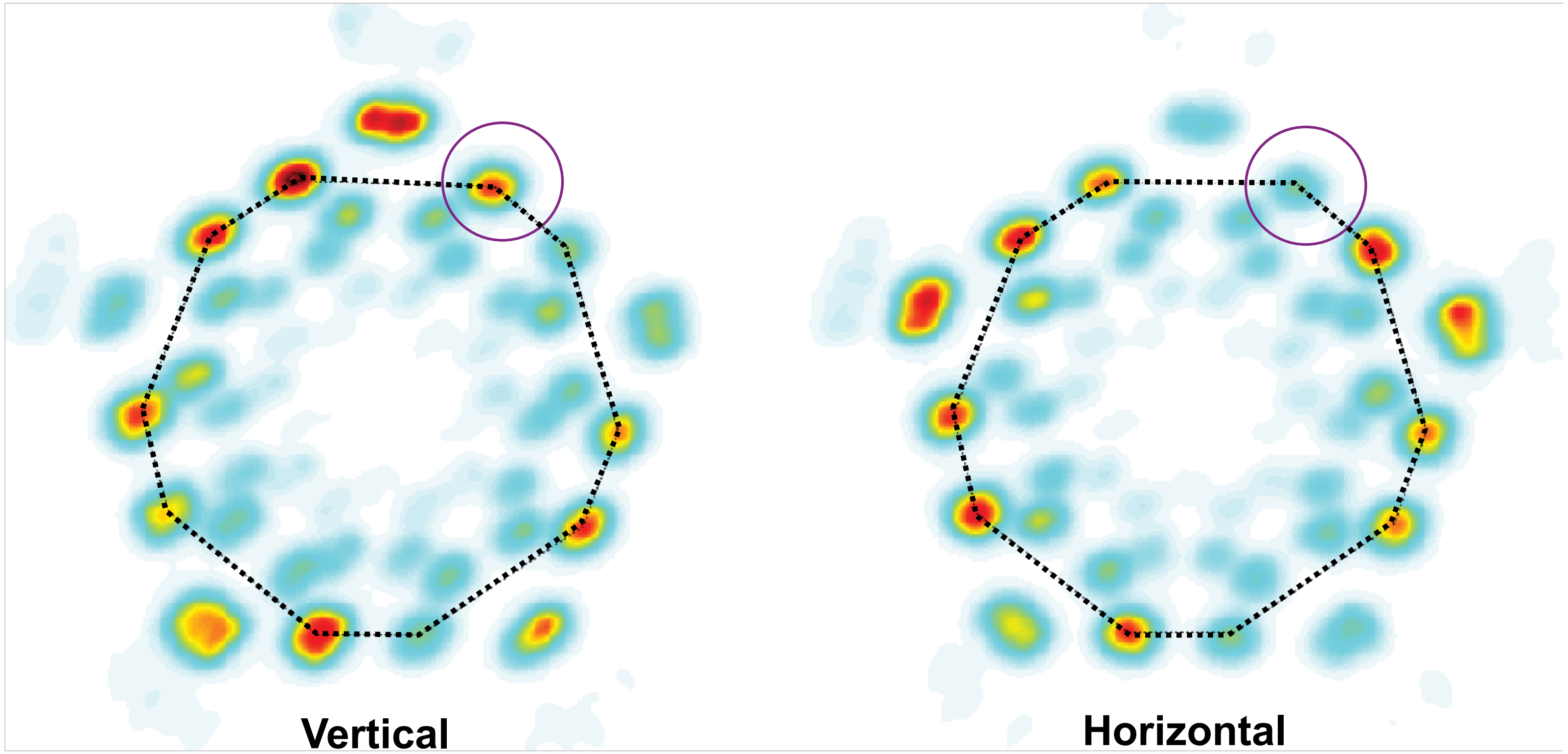

Vertical polarization

Horizontal polarization

E29546

The scattered light polarization was an important clue to the scattered light mystery

The usual suspects are unable to explain the nonuniformity and conventional implosion modeling can't explain the polarization of the scattered light

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Sources of nonuniformity

- Target Ice layer nonuniformity
  - Nonuniformity observed in warm implosions as well as CRYO
- Target offset
  - Nonuniformity observed in warm implosions as well as CRYO
- Beam Balance
  - Not large enough of an effect
- Beam Pointing
  - A strong contender but can't explain strong polarization of scattered light

Conventional hydrodynamic code CBET modeling

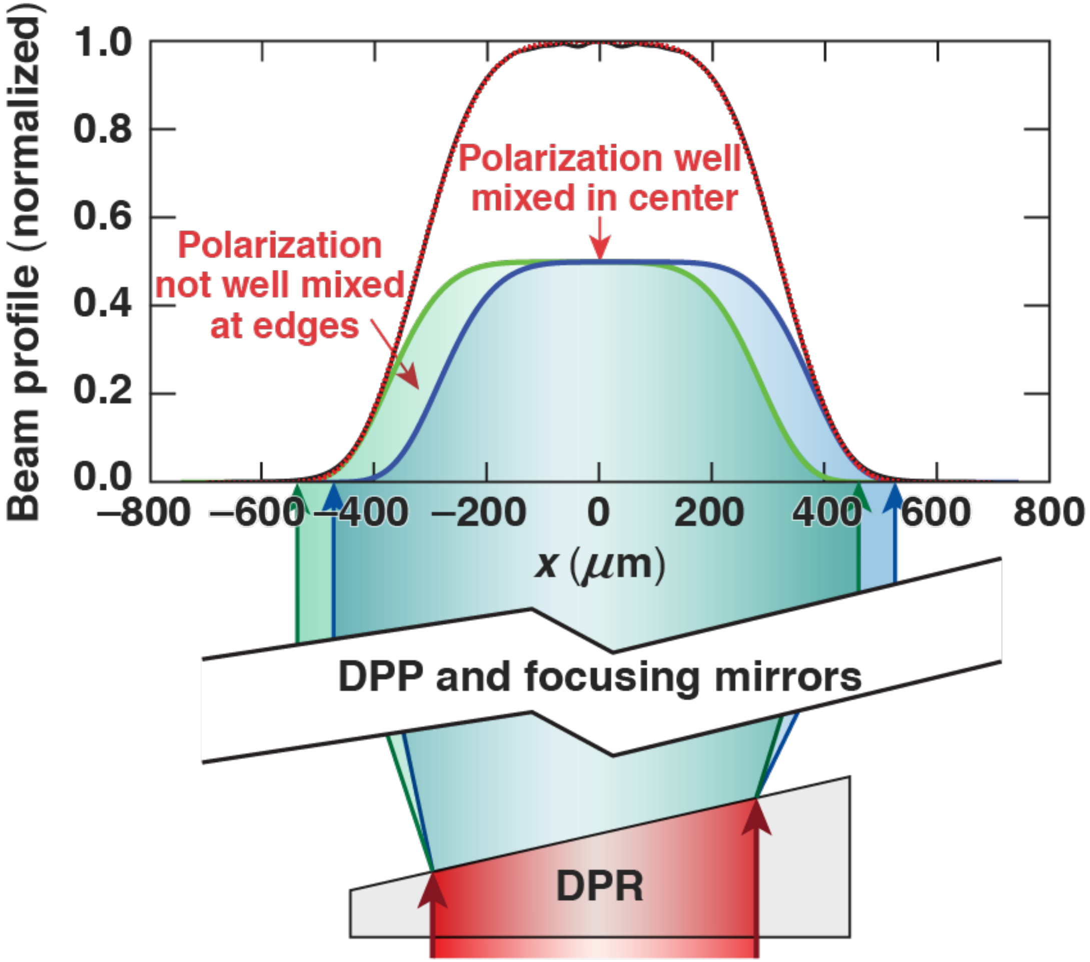
- Polarization smoothing assumed to give two equal but orthogonal polarizations throughout all beams
- Uses a simple factor to account for polarization effects between beams

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

- Predicts uniform 3wGOI beamlet spot intensities with evenly mixed polarizations

The measured scattered light polarization provided the clue for a previous unrealized source of nonuniformity.

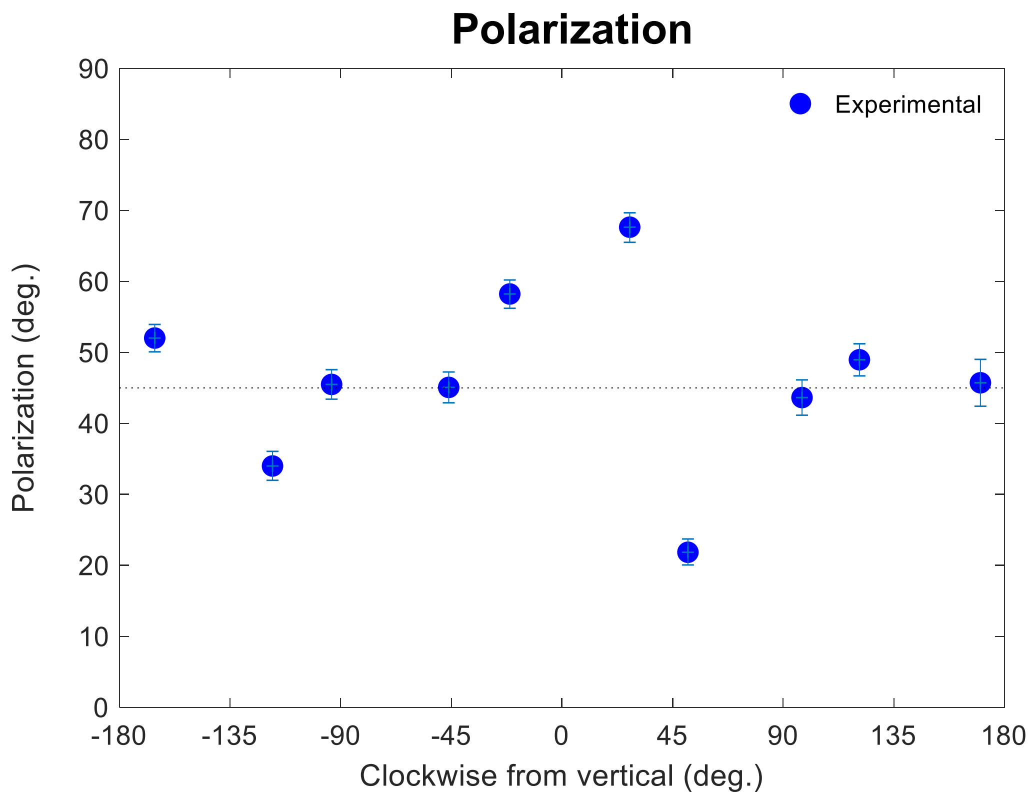
OMEGA's polarization smoothing scheme leads to strongly polarized regions

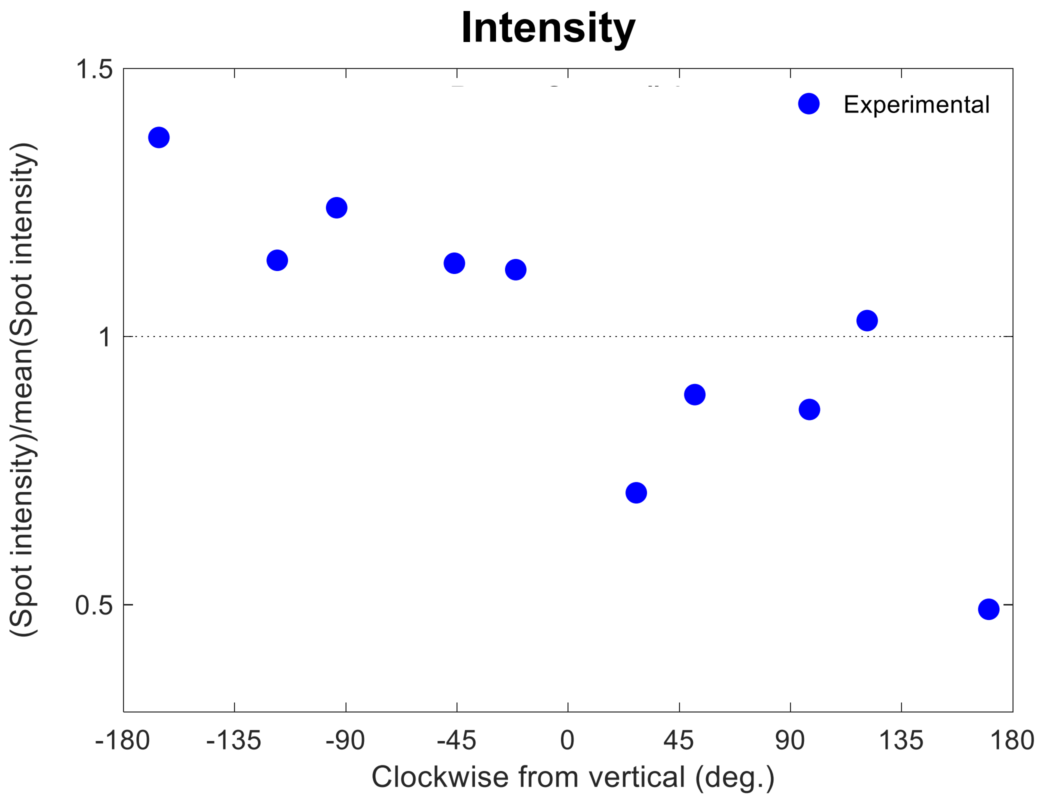


E29545

- 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
- Codes should treat each beam as two co-propagating beams with orthogonal polarization

Scattered light predictions are similar to the measurements, when the polarization effects are include in the 3-D CBET modeling*





* D. H. Edgell, et al., Phys. Rev. Letts. 127, 075001 (2021)

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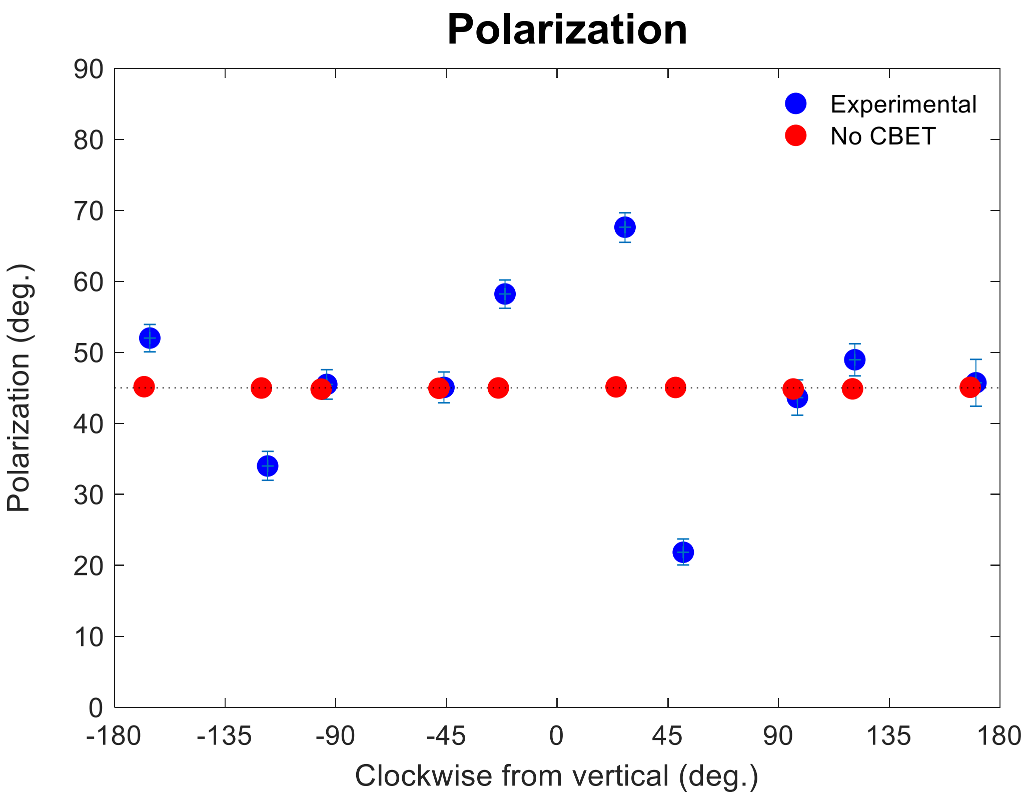
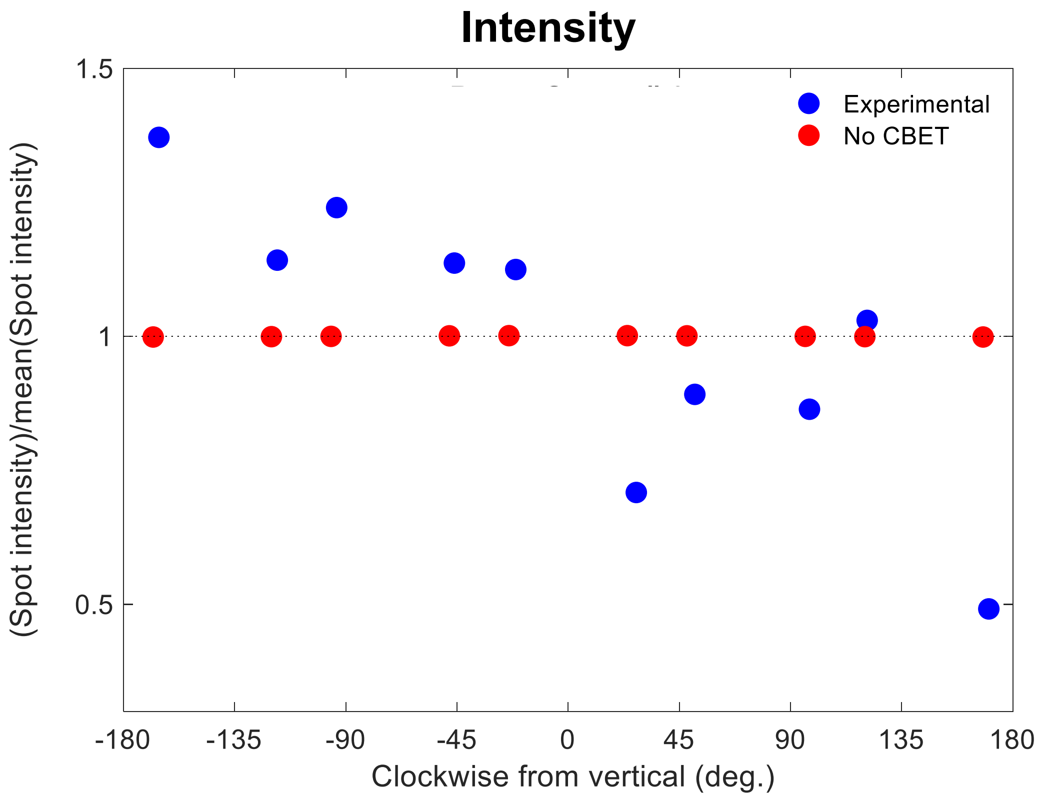
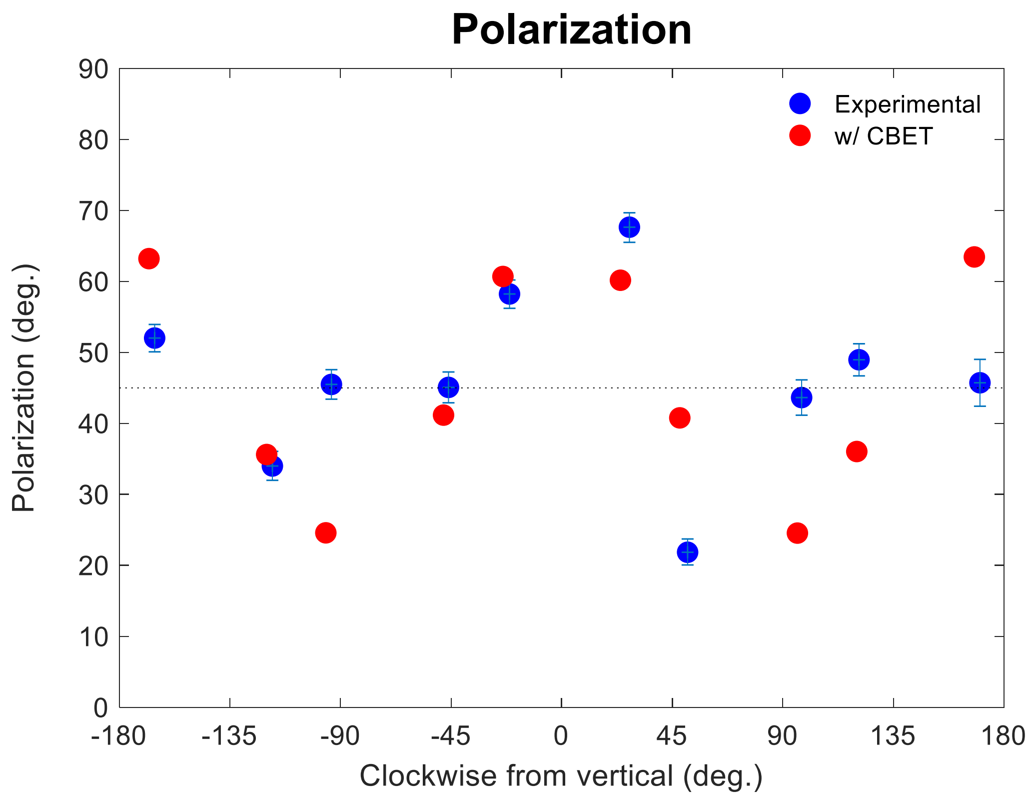


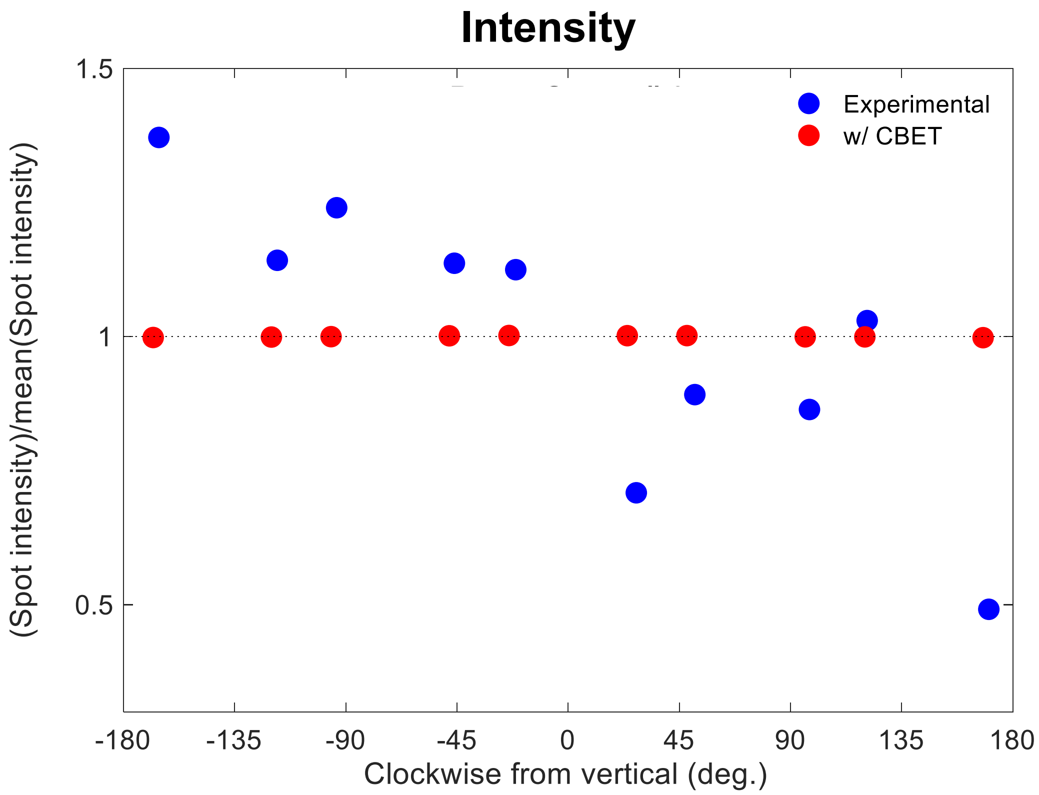


No CBET & No DPR split or CBET without polarization gives uniform predictions very different from measurements

* **D. H. Edgell, et al., Phys. Rev. Letts. 127, 075001 (2021)**
D. H. Edgell, et al., Physics of Plasmas 24, 062706 (2017);

Scattered light predictions are similar to the measurements, when the polarization effects are include in the 3-D CBET modeling*

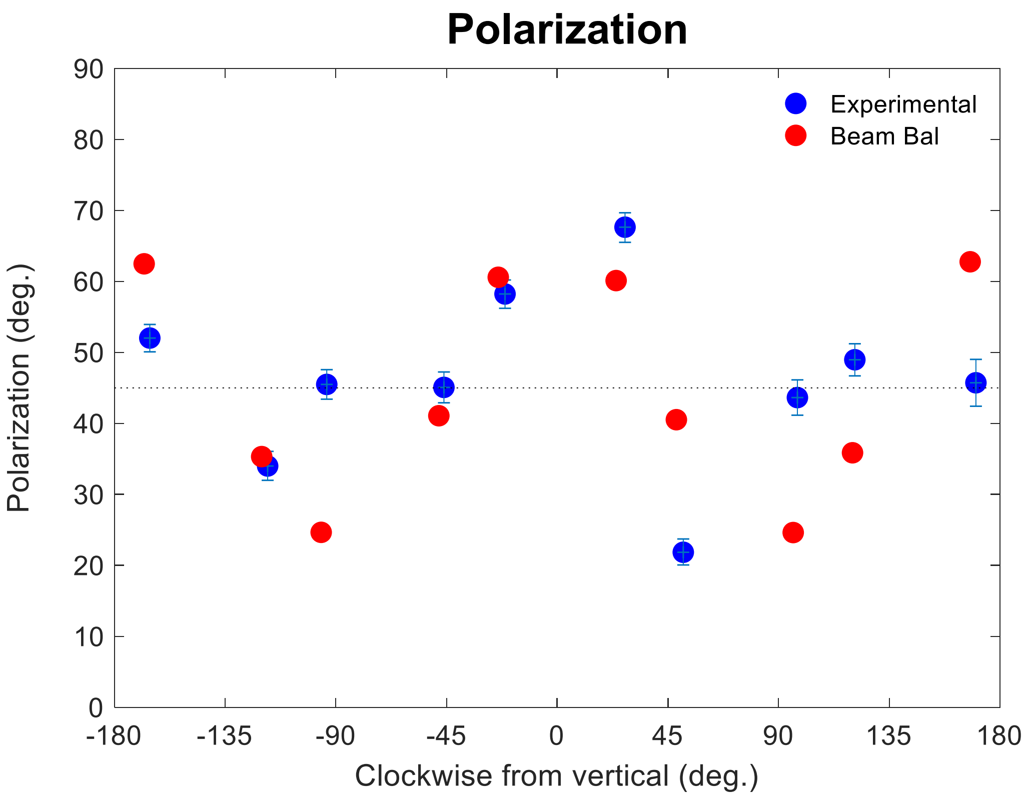


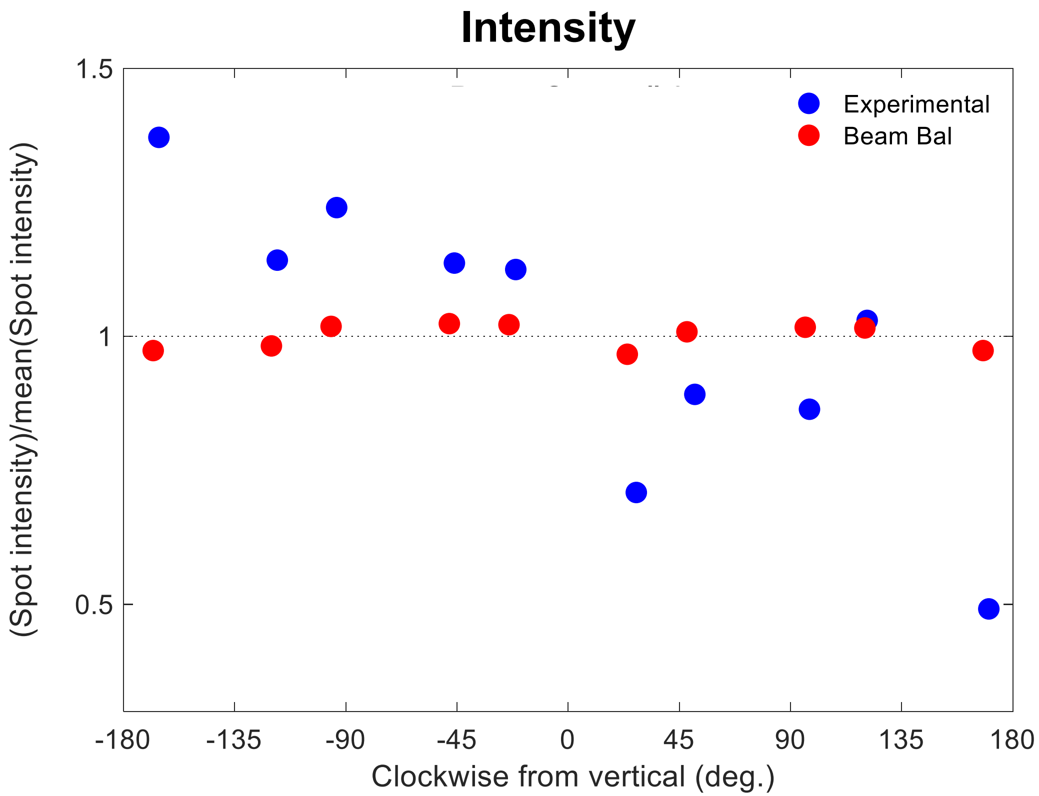


CBET with polarization (but no DPR shift) predicts uniform intensity and symmetric polarization rotation

* D. H. Edgell, et al., Phys. Rev. Letts. 127, 075001 (2021)

Scattered light predictions are similar to the measurements, when the polarization effects are include in the 3-D CBET modeling*

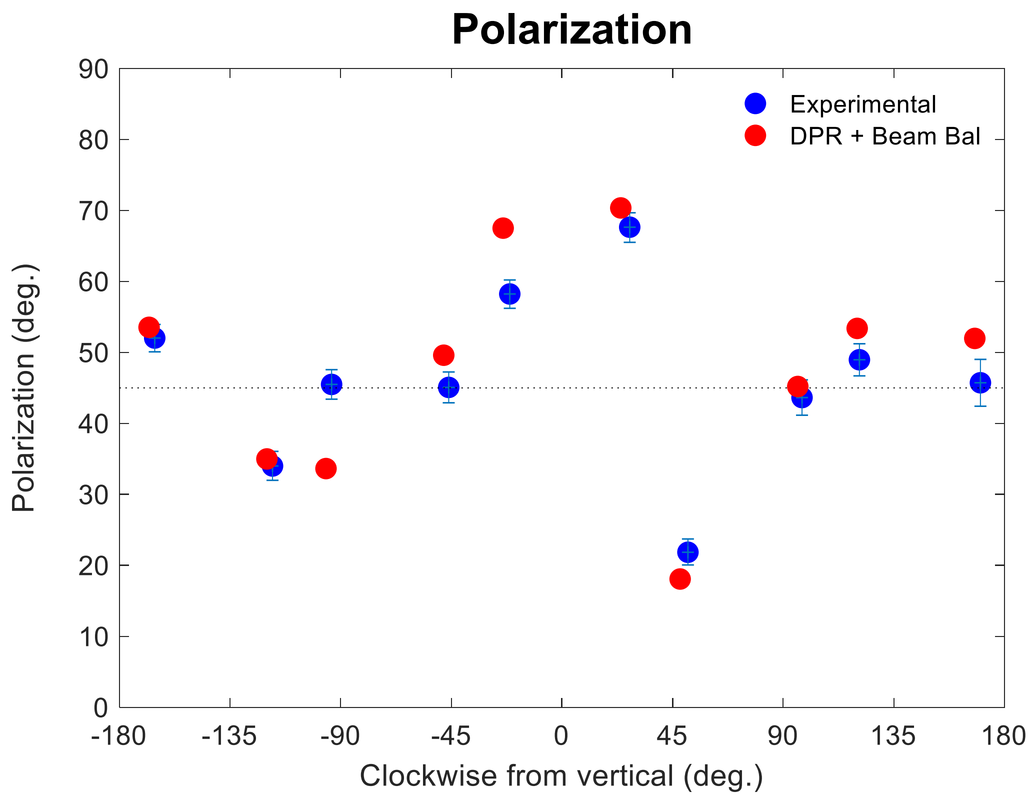


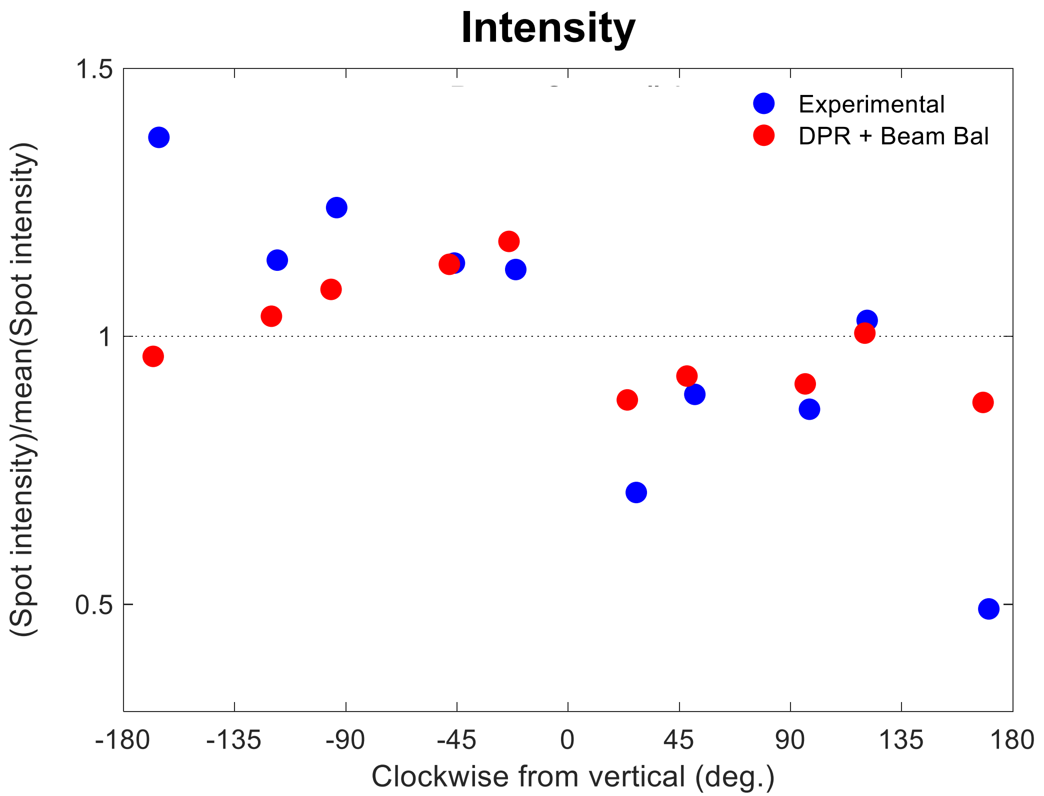


Including Beam Balance has only a small effect on the polarization and intensity predictions

* D. H. Edgell, et al., Phys. Rev. Letts. 127, 075001 (2021)

Scattered light predictions are similar to the measurements, when the polarization effects are include in the 3-D CBET modeling*

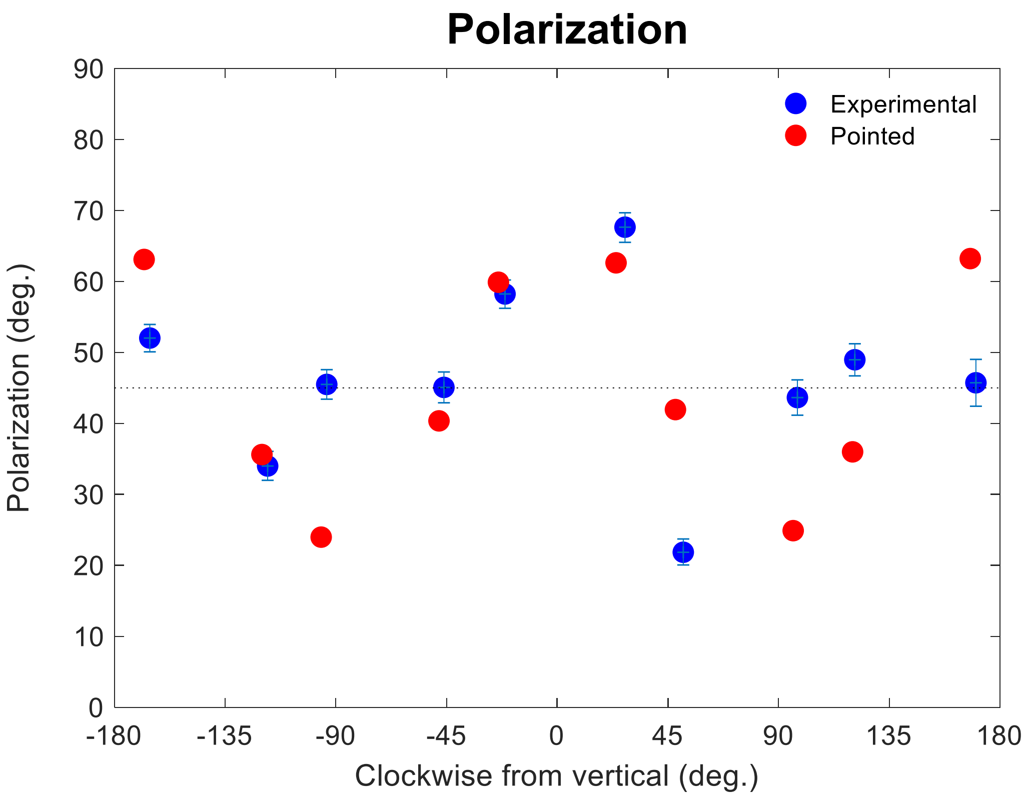


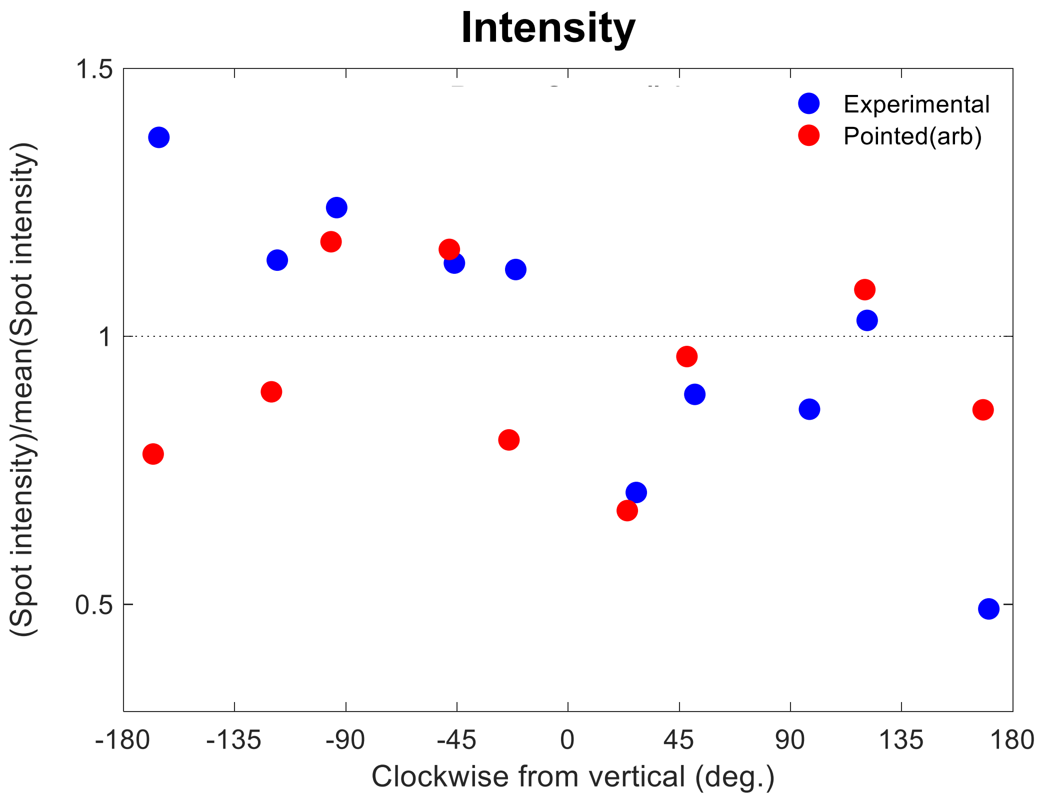


Including the DPR offset predicts polarizations that are very similar to the measurements.

* D. H. Edgell, et al., Phys. Rev. Letts. 127, 075001 (2021)

The remaining discrepancies in intensity are likely due to beam pointing



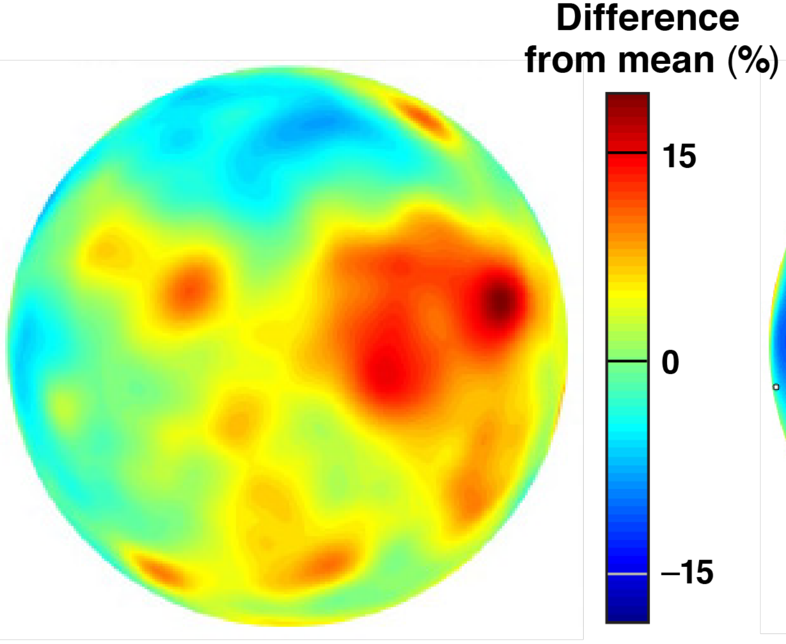


No precision beam pointing measurements were taken on this day.
Here we show the effect of "typical" beam pointing at the start of a day

* D. H. Edgell, et al., Phys. Rev. Letts. 127, 075001 (2021)

The full polarization CBET 3-D modeling predicts very nonuniform scattered light and absorption distributions

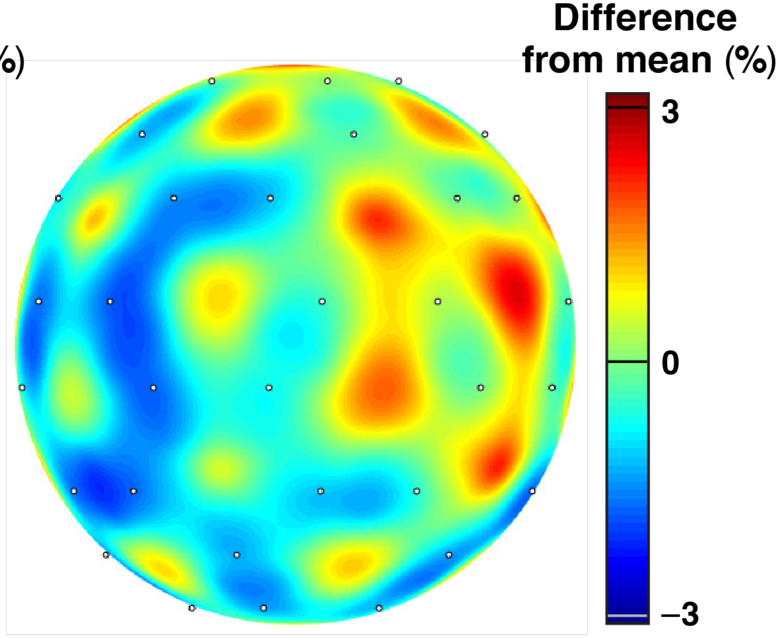
Scattered energy over chamber surface $\int P_{\mathrm{scat}}(\theta, \varphi, t)\mathrm{d}t$



E29856a

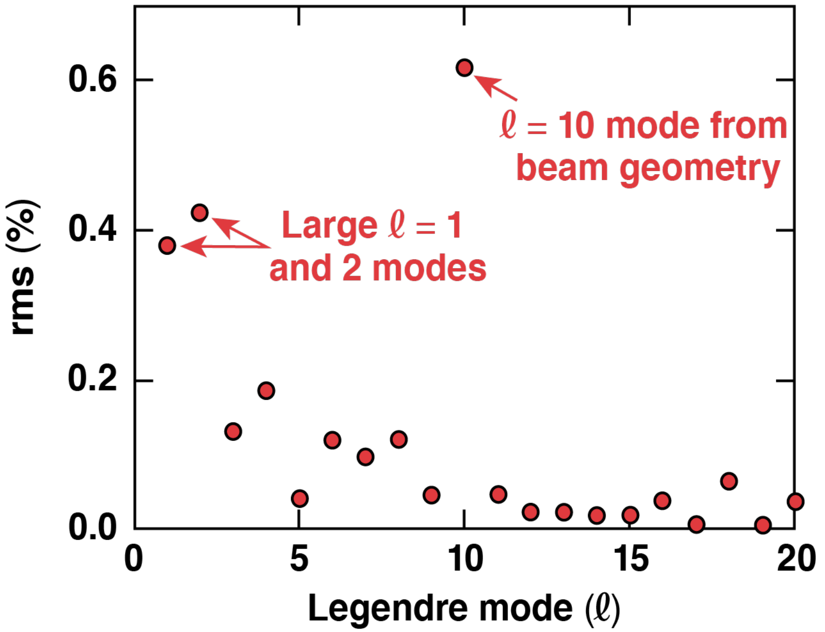
±5.42% rms
32.6% P-V

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



CBET polarization effects seem significant for scattered light but do they really affect implosion performance?

- **A recent campaign measured the core flow for well characterized implosions to compare with CBET modeling of the absorption mode 1**
  - **Warm Implosions – very small offsets from TCC**
  - **CRYO relevant beam energy and pulse shape**
  - **Precision Beam Pointing**
  - **w/ & w/o DPRs**

With DPRs out, all beams are linearly polarized and non circular so full 3-D modeling with beam pointing, beam balance and CBET polarization are required

- **DPRs out, SSD on**
  - **linearly polarized beams**
  - **non-circular beam spots**
  - **Core Flow: 104-126 km/s**

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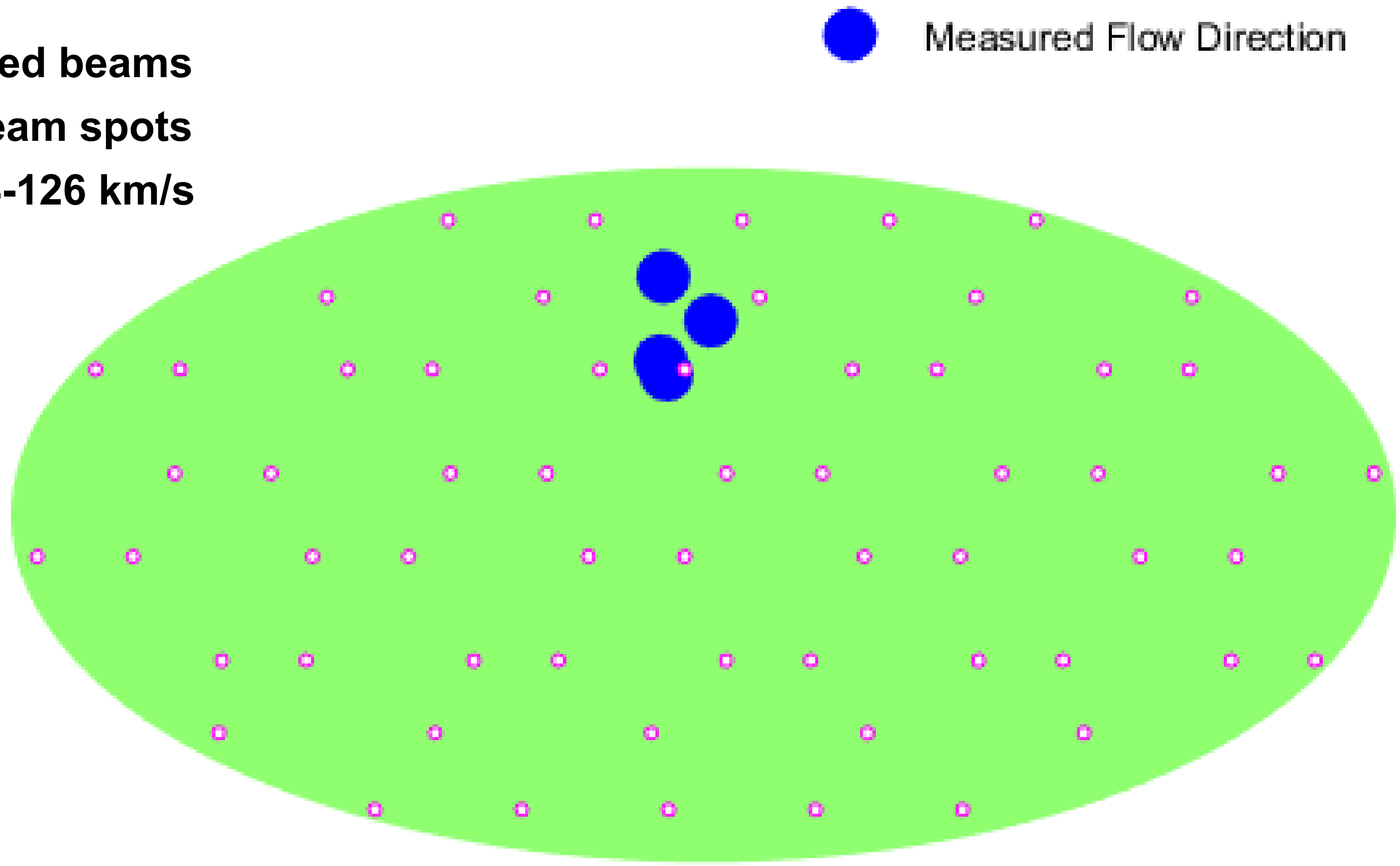

Mollweide projection

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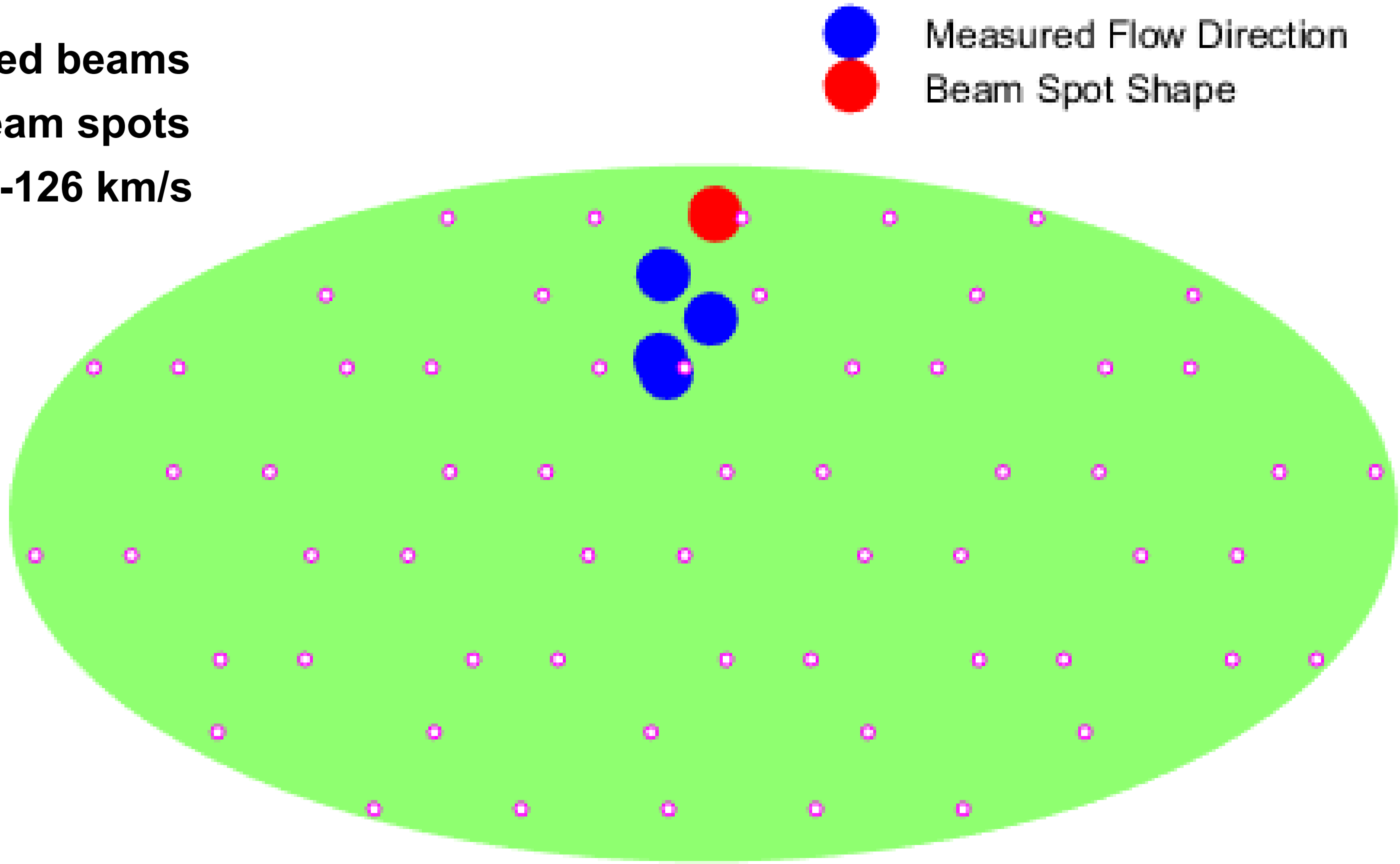

Mollweide projection

Mode 1 rms (%)

Beam Spot Shape 0.12

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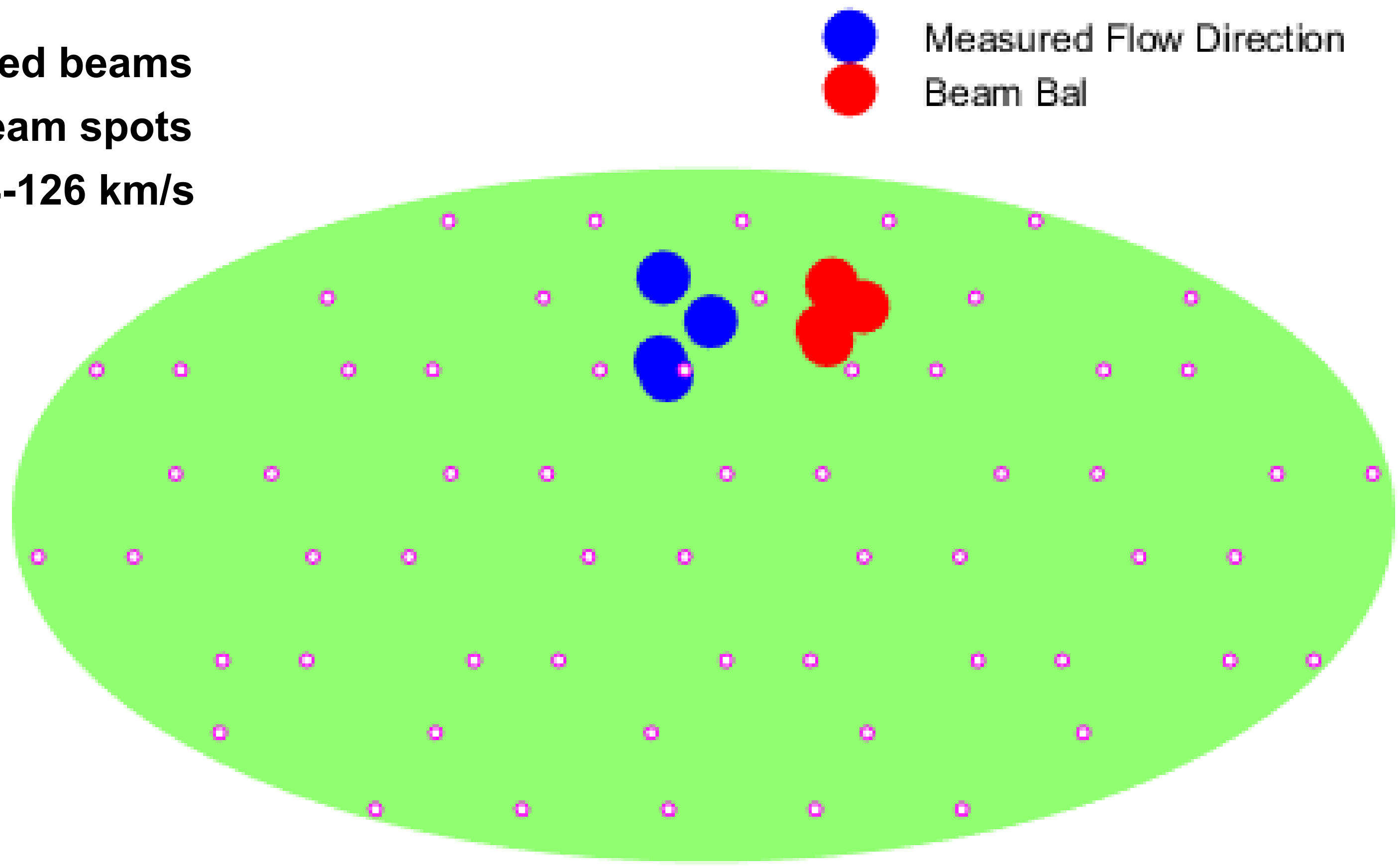


Mollweide projection

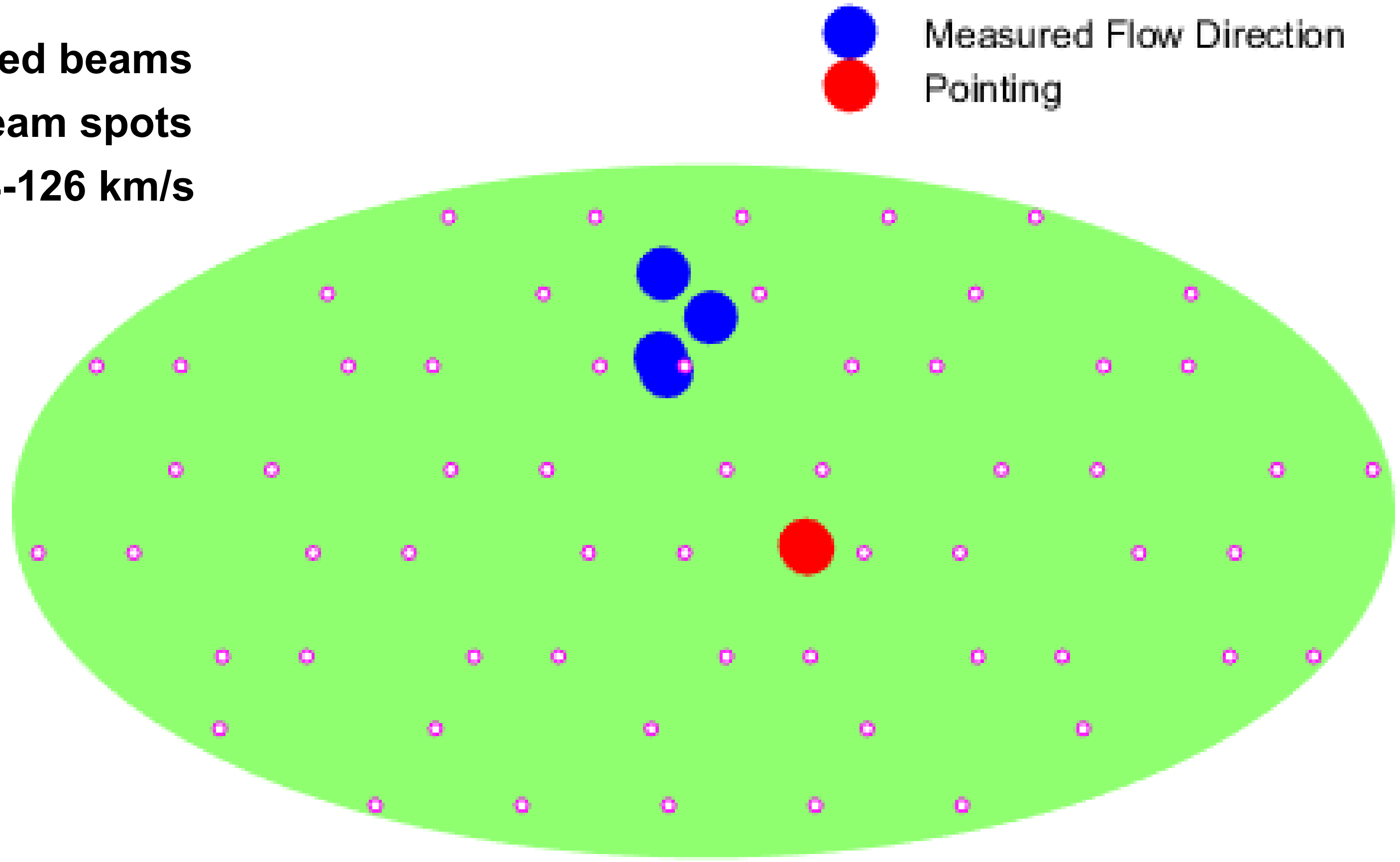
Mode 1 rms (%)

Beam Spot Shape 0.12

Beam Power Balance 0.61

With DPRs out, all beams are linearly polarized and non circular so full 3-D modeling with beam pointing, beam balance and CBET polarization are required

- DPRs out, SSD on
  - linearly polarized beams
  - non-circular beam spots
  - Core Flow: 104-126 km/s



Mollweide projection

Mode 1 rms (%)

Beam Spot Shape 0.12

Beam Power Balance 0.61

Beam Pointing 0.76

With DPRs out, all beams are linearly polarized and non circular so full 3-D modeling with beam pointing, beam balance and CBET polarization are required

- **DPRs out, SSD on**
  - **linearly polarized beams**
  - **non-circular beam spots**
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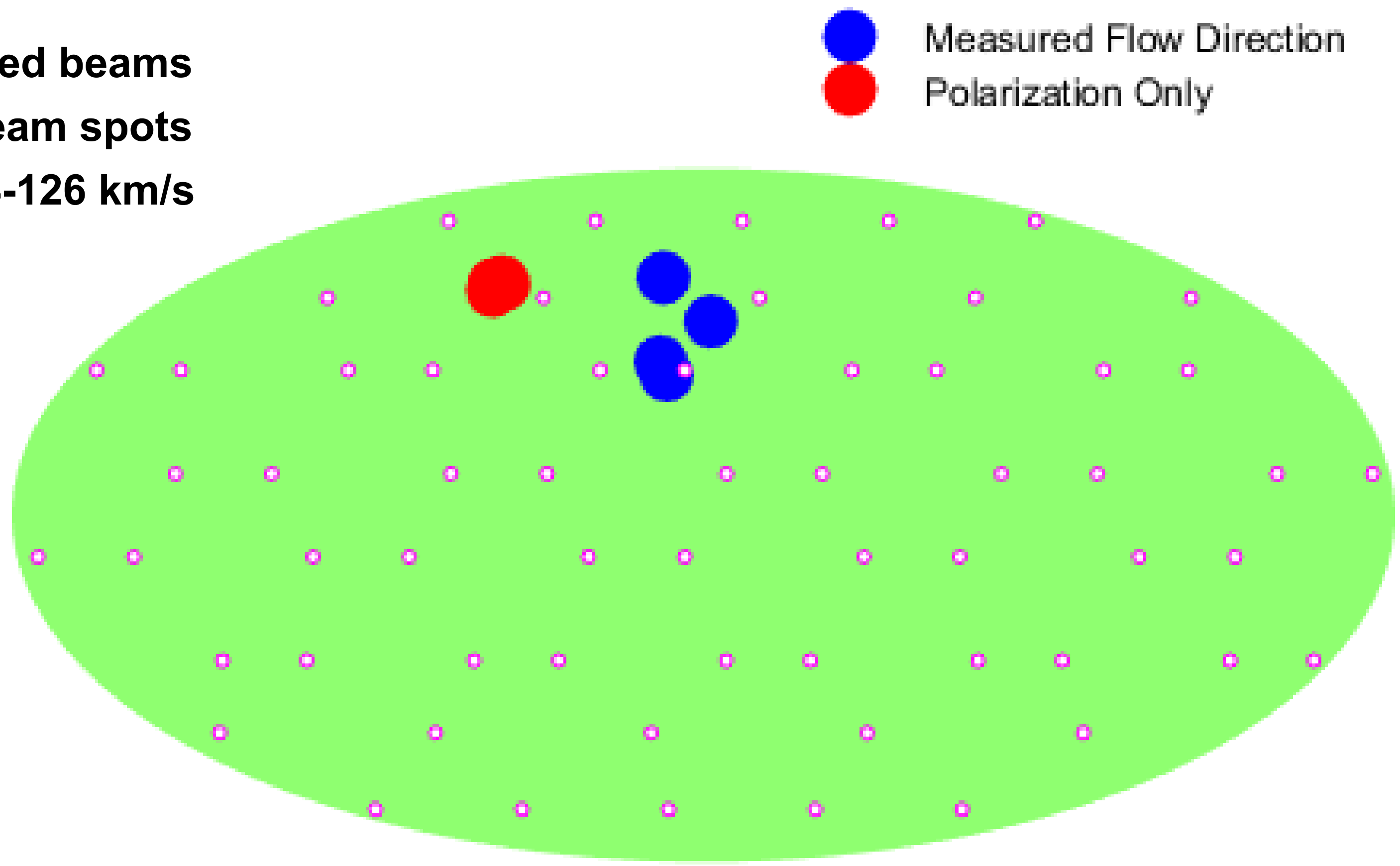

Mollweide projection

Mode 1 rms (%)

Beam Spot Shape 0.12

Beam Power Balance 0.61

Beam Pointing 0.76

Linear Polarization 0.67

With DPRs out, all beams are linearly polarized and non circular so full 3-D modeling with beam pointing, beam balance and CBET polarization are required

- DPRs out, SSD on
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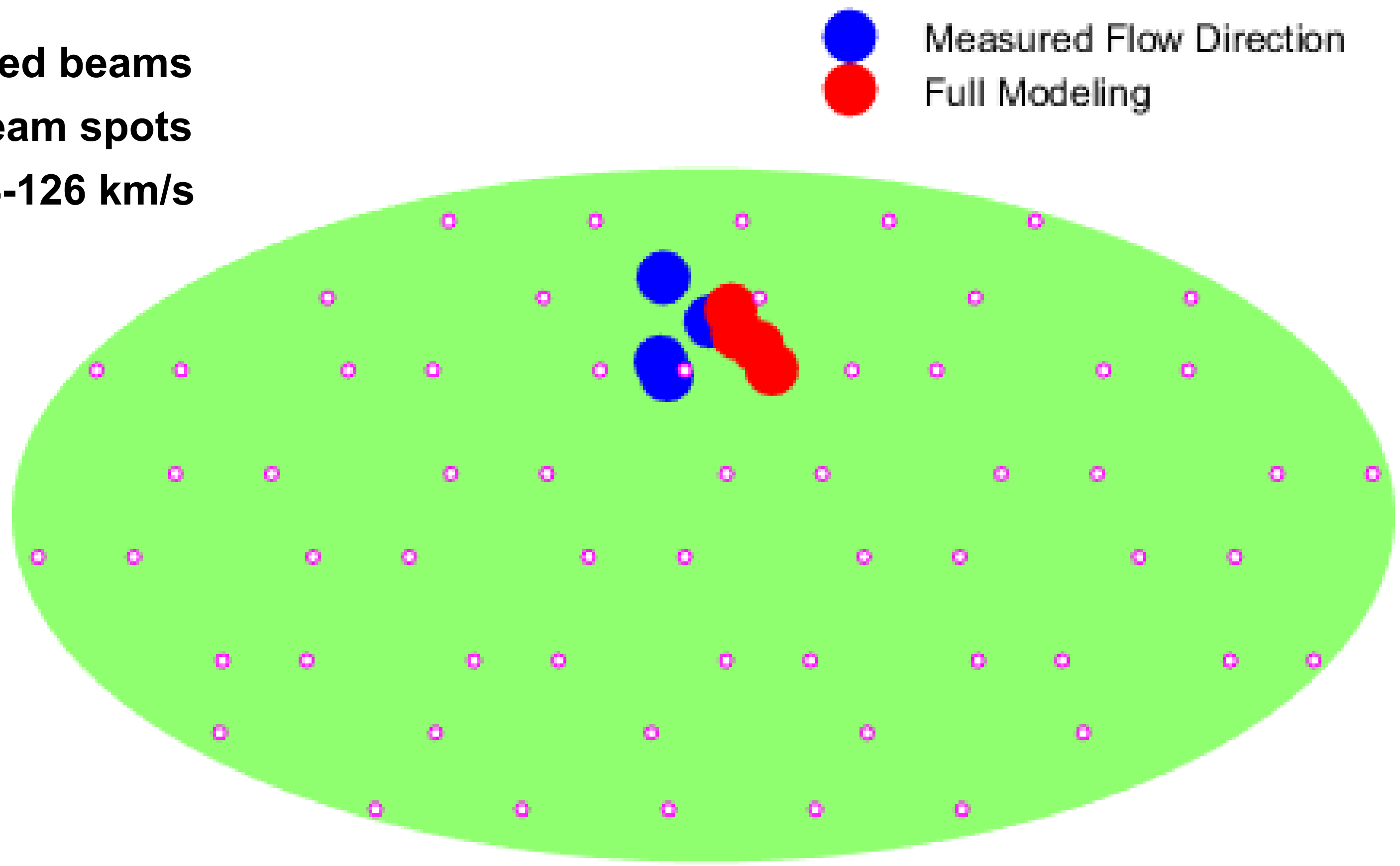
  - non-circular beam spots
  - Core Flow: 104-126 km/s



Mollweide projection

Mode 1 rms (%)

Beam Spot Shape 0.12

Beam Power Balance 0.61

Beam Pointing 0.76

Linear Polarization 0.67

All of the Above 1.21

DPR polarization smoothing implosions also require full 3-D modeling with beam pointing, beam balance and CBET polarization to predict flow direction

- DPRs in, SSD on
  - partially polarized beams
  - circular beam spots
  - Core Flow: 84-97 km/s

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- DPRs in, SSD on
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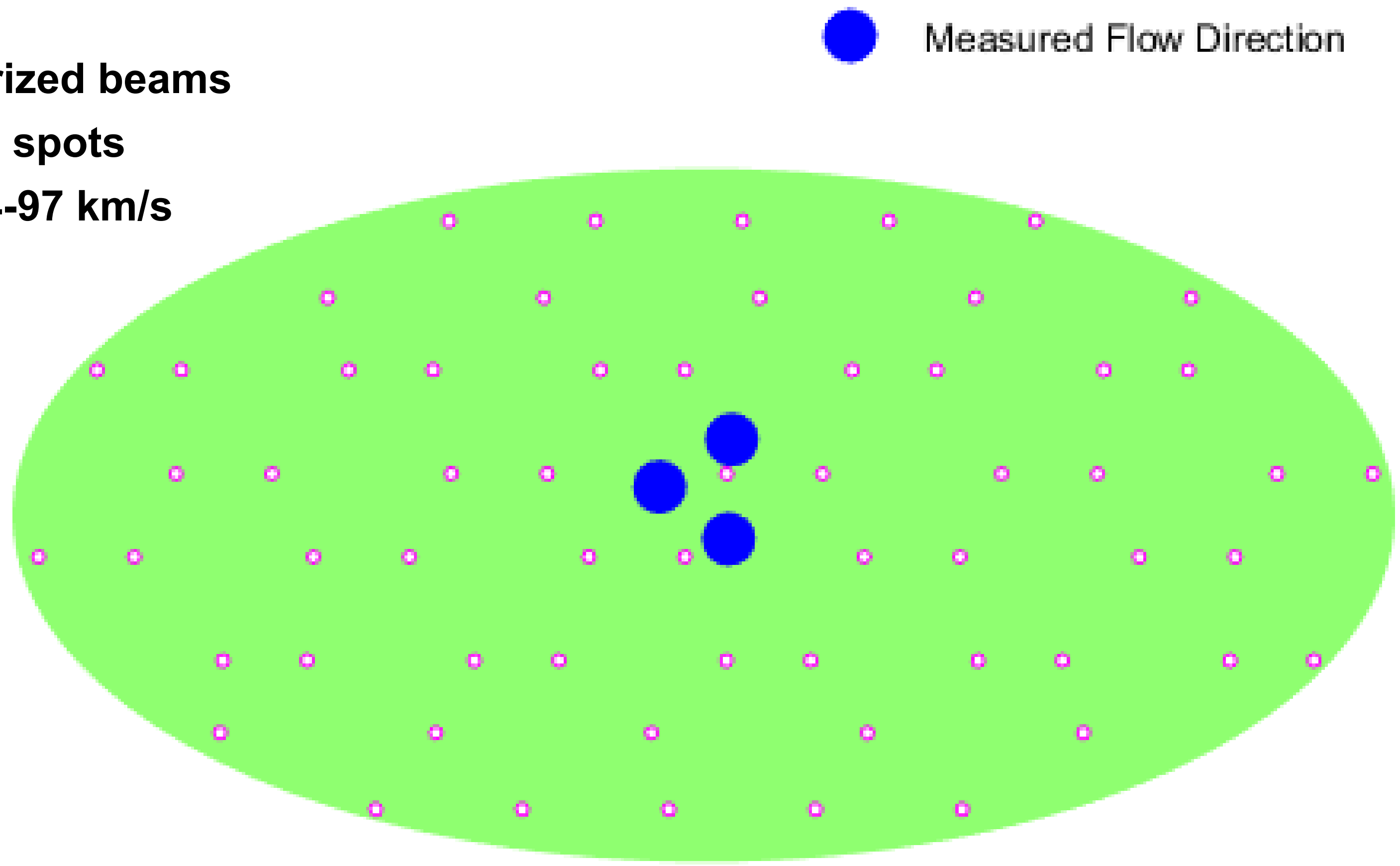
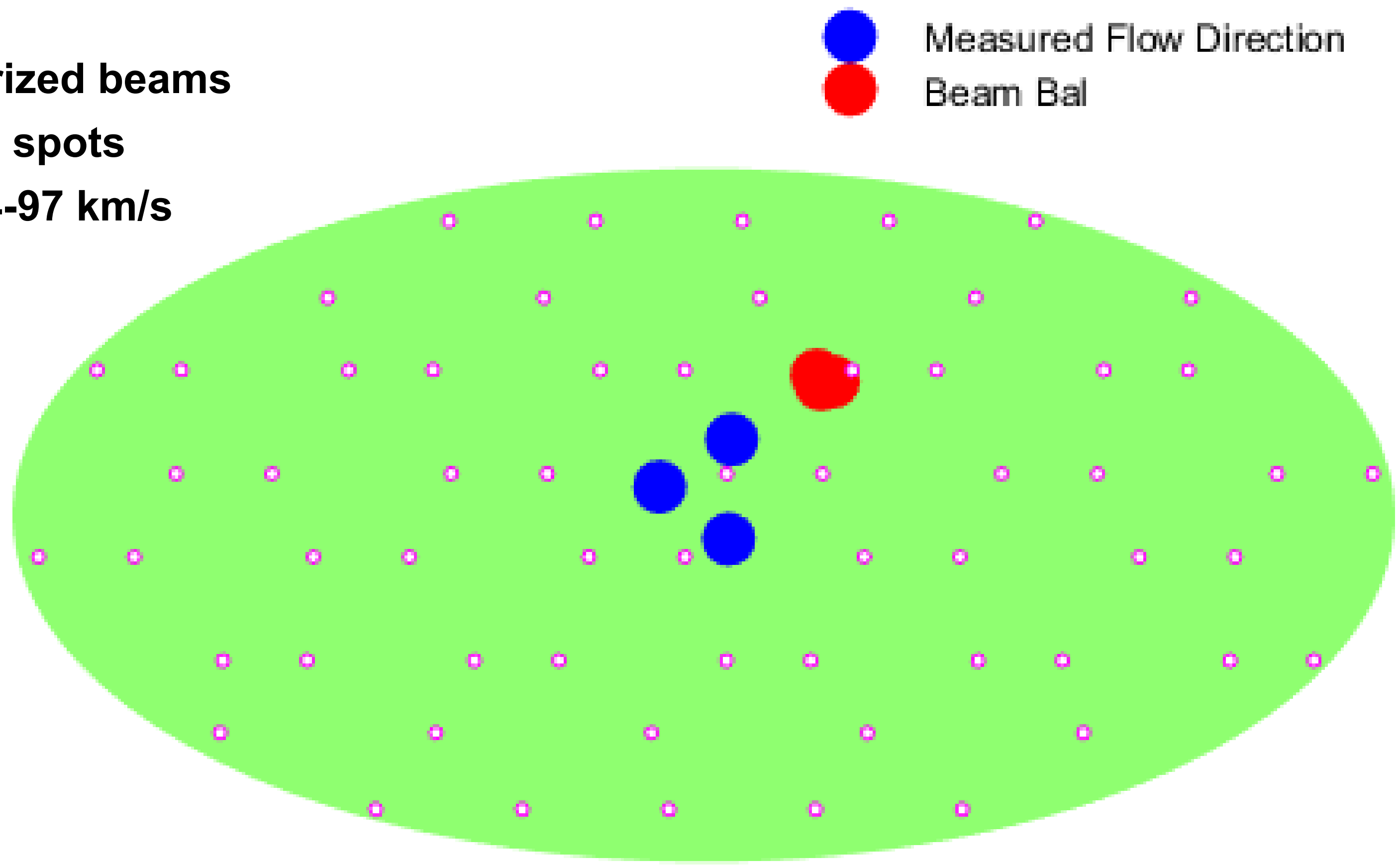
  - Core Flow: 84-97 km/s



Mollweide projection

Predicted mode 1 is similar to the measured flow directions with DPRs in, when beam pointing, beam balance and CBET polarization are 3-D modeled

- **DPRs in, SSD on**
  - partially polarized beams
  - circular beam spots
  - Core Flow: 84-97 km/s



Mollweide projection

Mode 1 rms (%)

Beam Power Balance 0.65

Predicted mode1 are similar to the measured flow directions with DPRs in, when beam pointing, beam balance and CBET polarization are 3-D modeled

- DPRs in, SSD on
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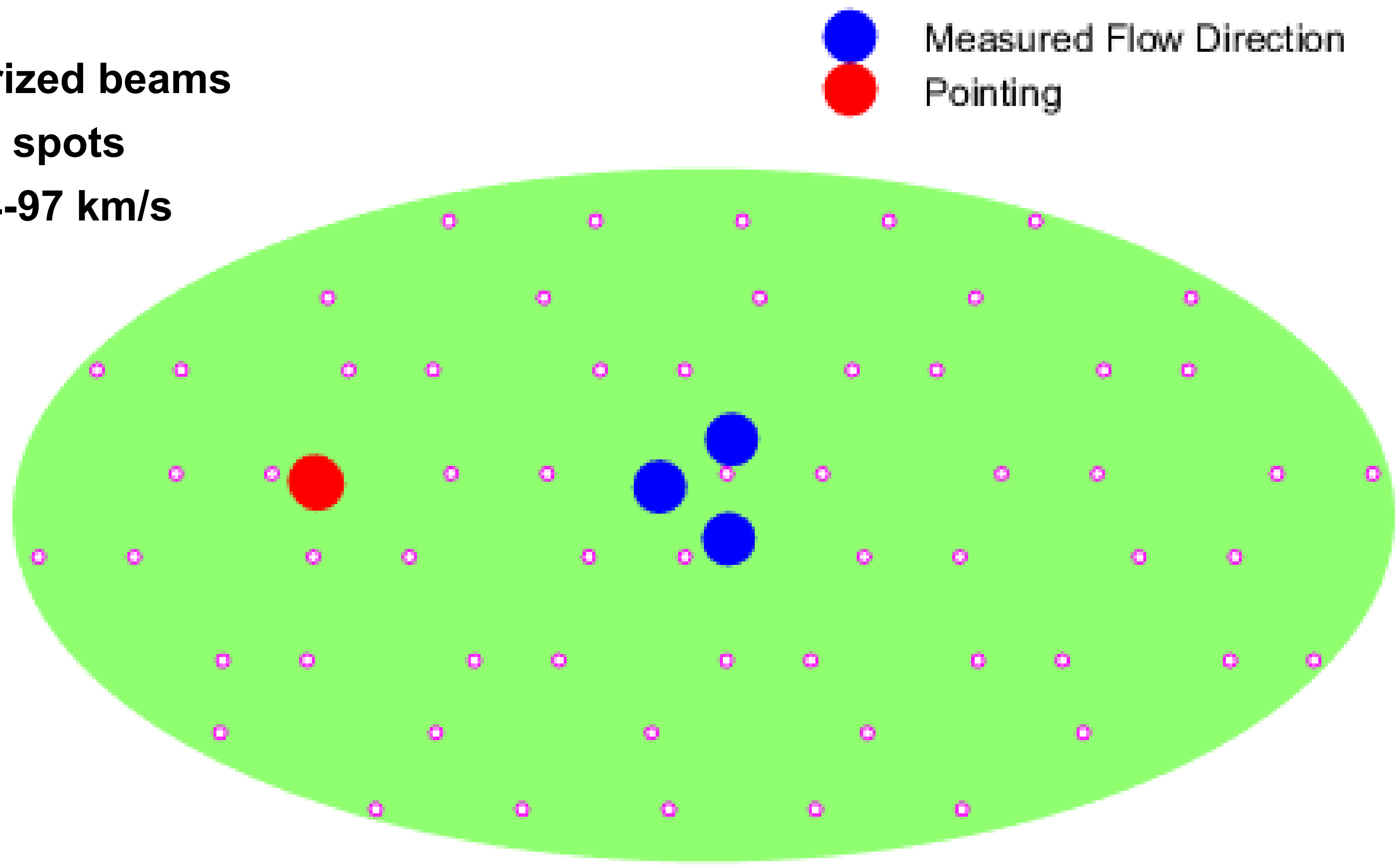


Mollweide projection

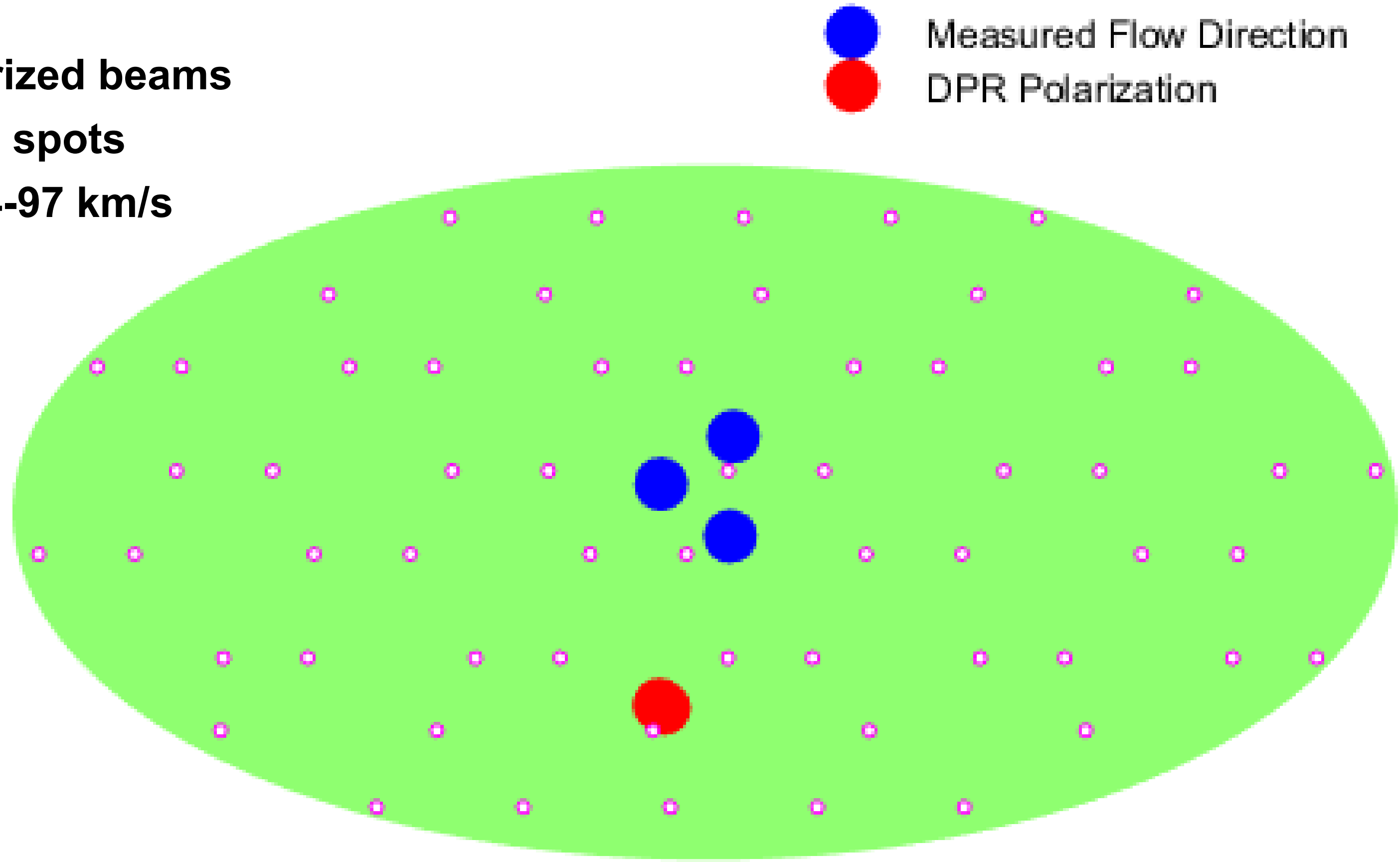
Mode 1 rms (%)

Beam Power Balance 0.65

Beam Pointing 0.56

Predicted mode 1 is similar to the measured flow directions with DPRs in, when beam pointing, beam balance and CBET polarization are 3-D modeled

- **DPRs in, SSD on**
  - **partially polarized beams**
  - **circular beam spots**
  - **Core Flow: 84-97 km/s**



Mollweide projection

Mode 1 rms (%)

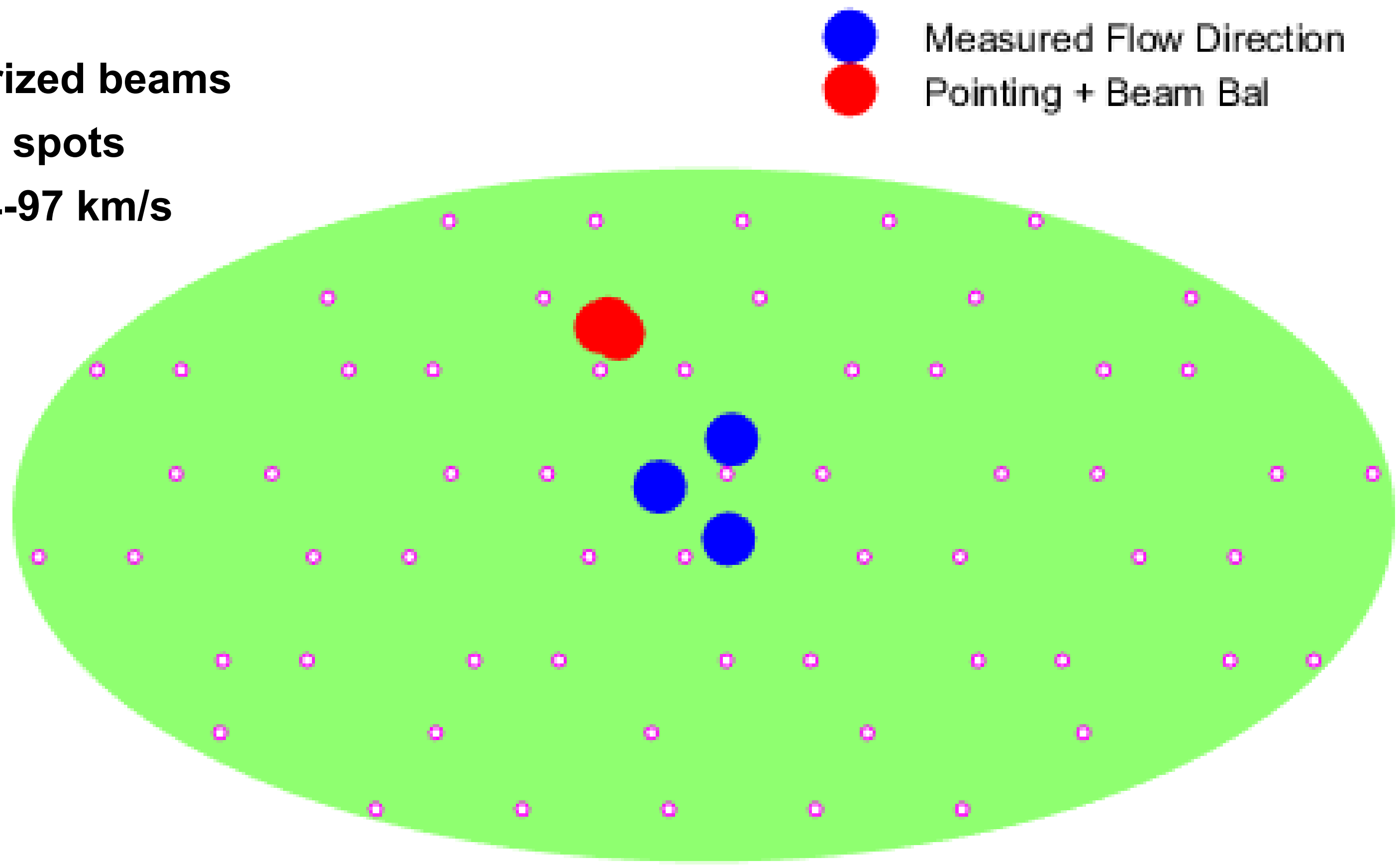
Beam Power Balance 0.65

Beam Pointing 0.56

DPR Polarization 0.39

Predicted mode 1 is similar to the measured flow directions with DPRs in, when beam pointing, beam balance and CBET polarization are 3-D modeled

- DPRs in, SSD on
  - partially polarized beams
  - circular beam spots
  - Core Flow: 84-97 km/s



Mollweide projection

Mode 1 rms (%)

Beam Power Balance 0.65

Beam Pointing 0.56

DPR Polarization 0.39

Pointing + Beam Bal 0.56

Predicted mode 1 is similar to the measured flow directions with DPRs in, when beam pointing, beam balance and CBET polarization are 3-D modeled

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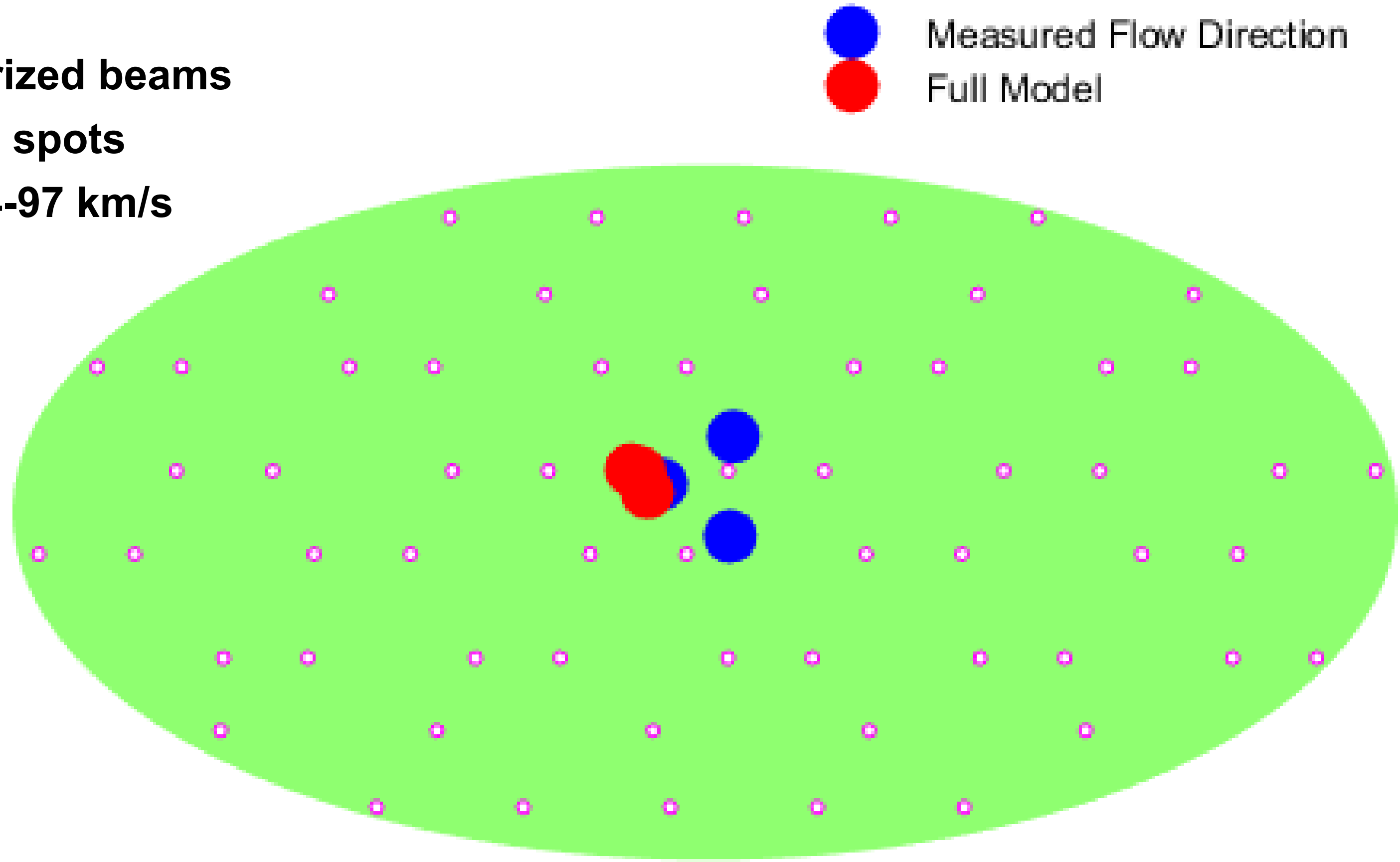


Mollweide projection

Mode 1 rms (%)

Beam Power Balance 0.65

Beam Pointing 0.56

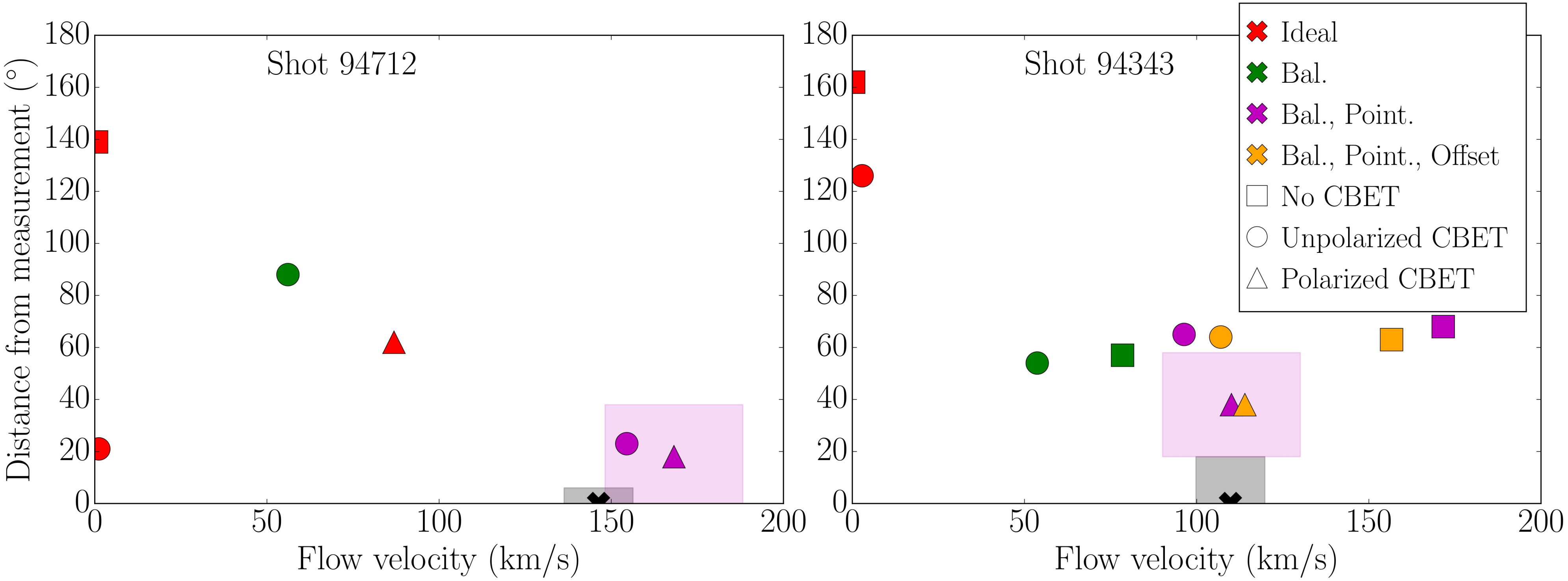
DPR Polarization 0.39

Pointing + Beam Bal 0.56

All of the Above 0.69

A fully 3-D radiative hydrodynamic code with polarized CBET similarly predicts the core flow for OMEGA implosions*

- **The modeling shown previously post-processes 1-D hydrodynamic simulations so the 3-D and polarization effects are not coupled to the hydrodynamics**
- **When the 3-D and polarization effects are integrated into a 3-D radiation-hydrodynamic code the bang time, neutron yield, and core flow predictions (purple triangles) matched measurements (grey zones) well.**



* A. Colaïtis, this conference & submitted to Phys. Rev. Letts.

Summary

Three dimensional polarization-dependent CBET plus beam balance and pointing are required to model nonuniformity in direct-drive implosions on OMEGA

- **Uniform laser energy absorption is essential for successful laser-direct-drive inertial confinement fusion but a growing body of evidence 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**
- **Polarization-dependent CBET along with beam energy balance, and beam pointing require three-dimensional modeling**
- **Laser absorption mode 1 predictions from a fully three-dimensional CBET model correlate well with the observed direction of the core flow.**