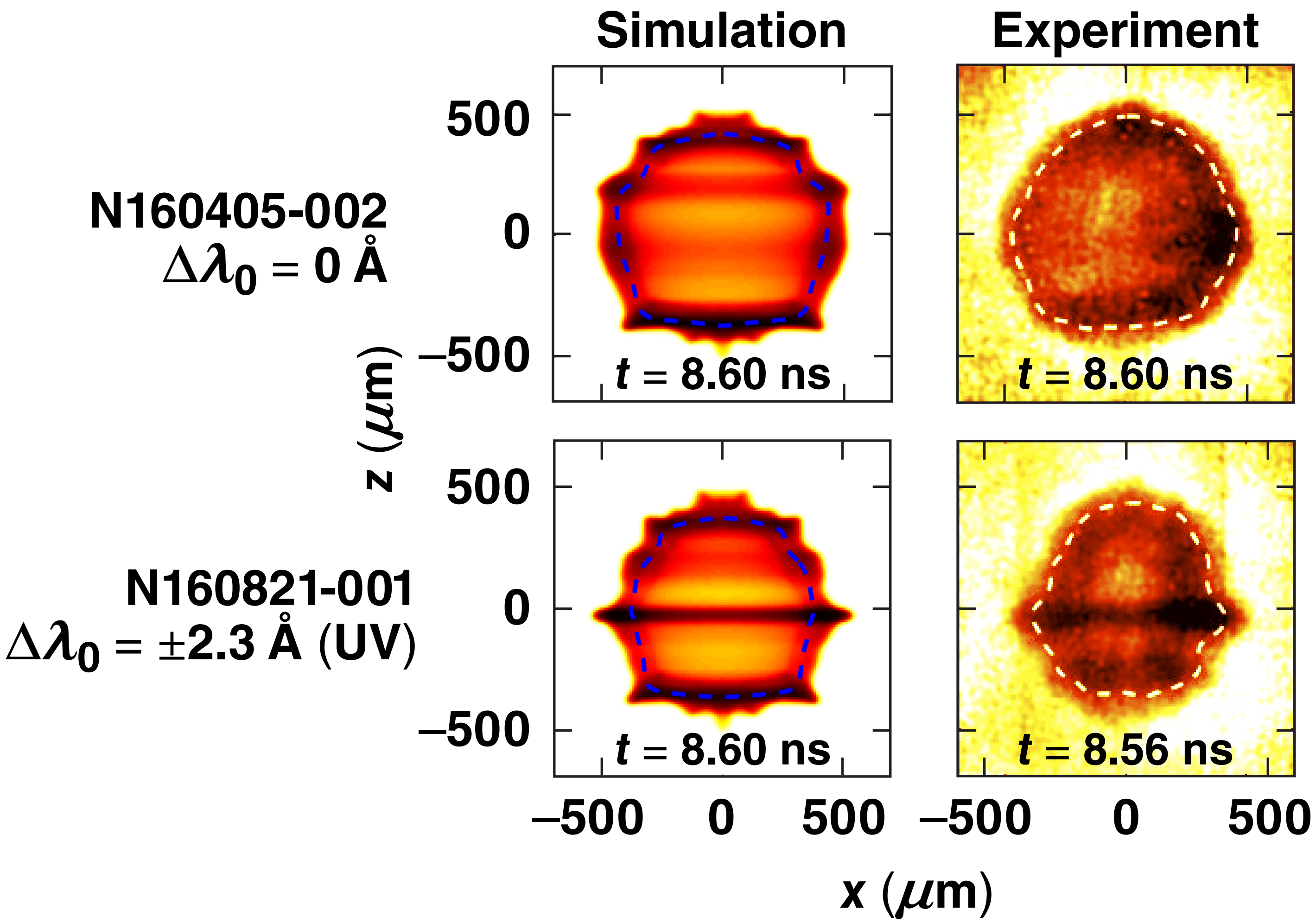
Wavelength Detuning Cross-Beam Energy Transfer Mitigation for Polar and Symmetric Direct Drive



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Summary

Initial wavelength-detuning experiments at the National Ignition Facility (NIF) successfully demonstrated cross-beam energy transfer (CBET) mitigation in polar direct drive (PDD)

- The first wavelength-detuning experiments measured changes in shape, shell trajectory, and scattered light as predicted by simulations
  - e.g., the predicted equatorial mass accumulation was observed, which is a by-product of efficient equatorial drive with non-optimal spot shapes and a nearly "round" shell in PDD
- The successful NIF wavelength-detuning experiments lay the foundation for future advances: larger $\Delta\lambda_0$, multiple wavelengths, flexible wavelength distribution, optimized spot shapes, etc.

TC12955

Collaborators

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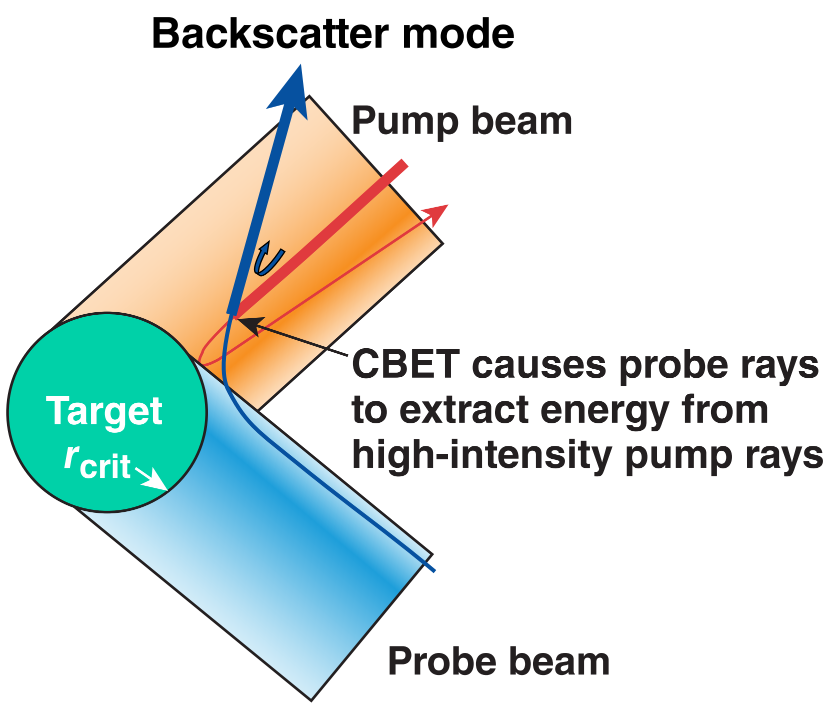
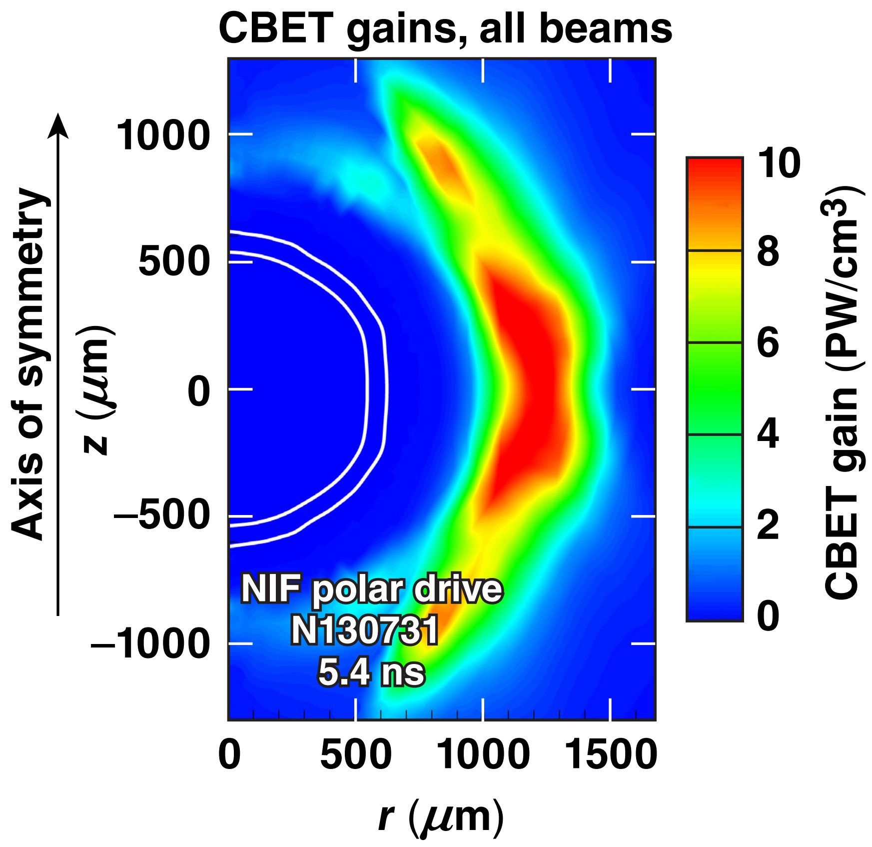
The majority of CBET occurs over the equatorial region in PDD



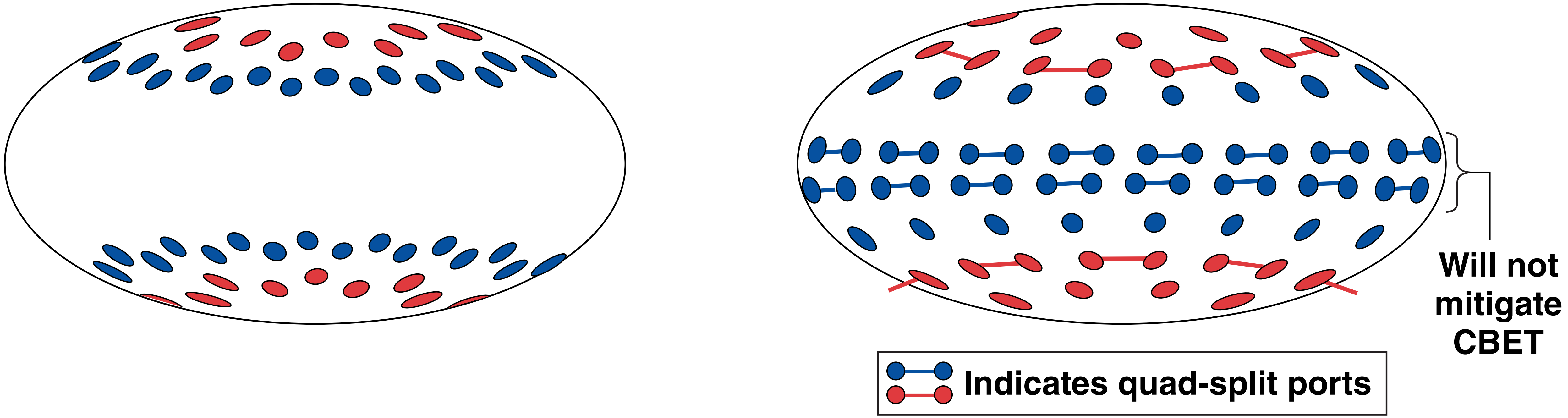


CBET mitigation in PDD predominantly affects the equatorial region.

- CBET reduces the laser drive by as much as 30%, making CBET mitigation the most important design issue
- Equatorial beams dominate the CBET interaction in PDD
- Wavelength detuning and spot-masking apodization (SMA) significantly mitigate CBET and provide a path for higher convergence
  - these combined mitigation methods can be used on symmetric direct drive (SDD) and PDD

Cone swapping in one hemisphere on the NIF induces the desired wavelength difference around the equator

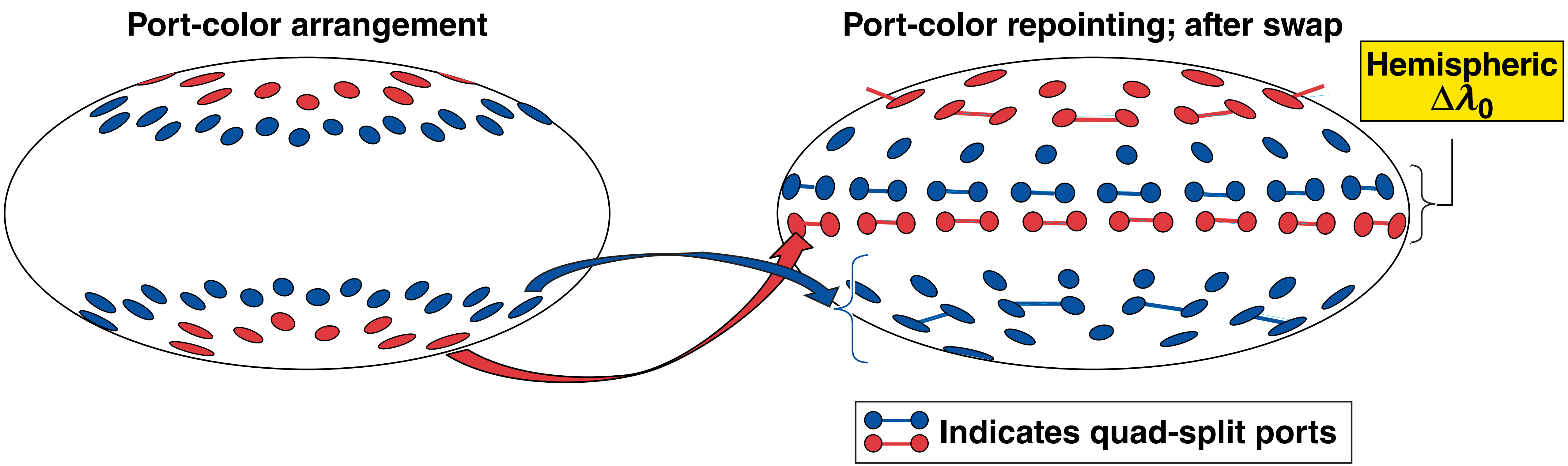
Port-color arrangement **Port-color repointing; normal PDD**



- Two colors are assigned in the NIF's current configuration: Cones 1 and 2 are red shifted; Cone 3 is blue shifted
- When ports are repointed in the typical PDD manner, identical colors cover the equator
  - this configuration will not mitigate CBET

TC11736h

Cone swapping in one hemisphere on the NIF induces the desired wavelength difference around the equator

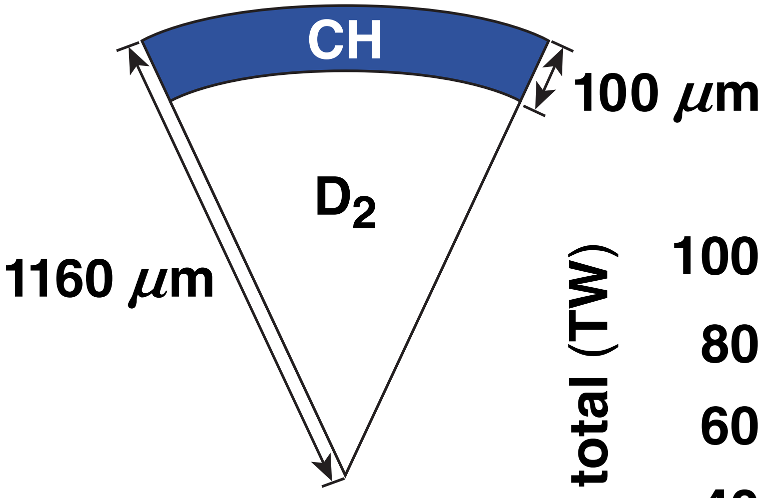


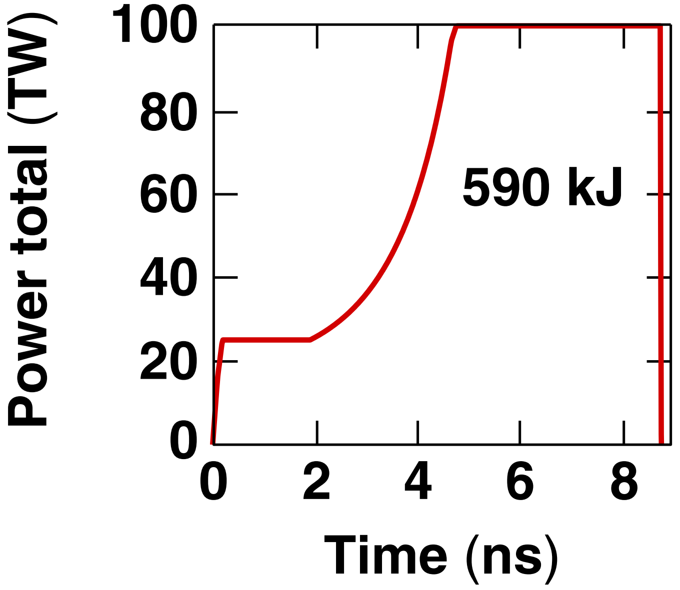
- Only a modest $\Delta\lambda_0 = \pm 2.3$ Å (UV) detuning is available in the current configuration
  - mitigation strategies for armor-glass metal clips will alleviate this constraint
- Cone swapping in one hemisphere was necessary to induce a wavelength difference over the equator
  - side effect is an asymmetric configuration with nonideal equatorial spot shapes
  - a reconfiguration of the fiber front end will alleviate this constraint

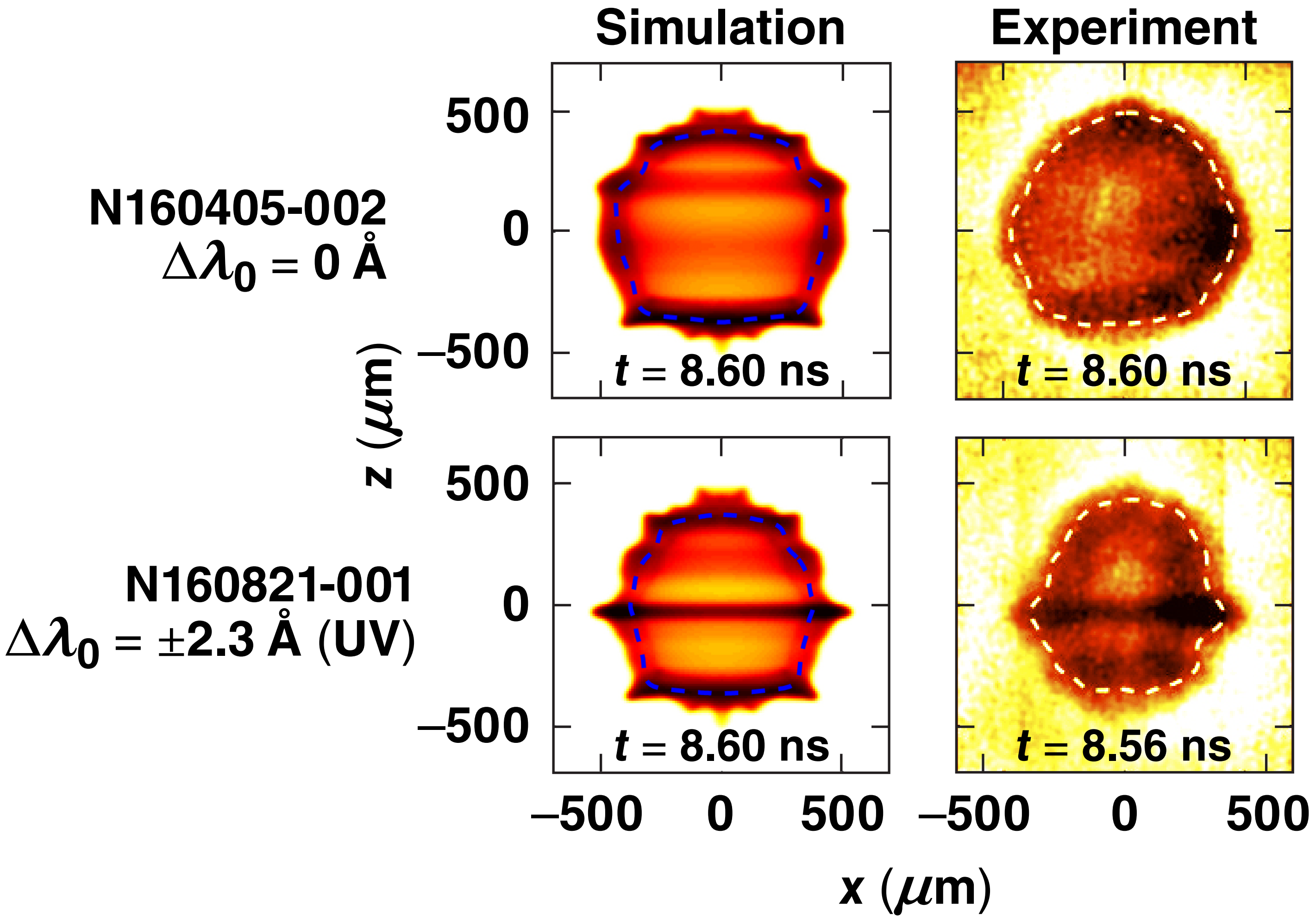
TC11736i

The first cone-swapping wavelength-detuning experiments on the NIF demonstrated CBET mitigation

NIF cone-swapping $\Delta\lambda_0$ campaign:
Designer: J. A. Marozas
RI: M. Hohenberger/M. J. Rosenberg



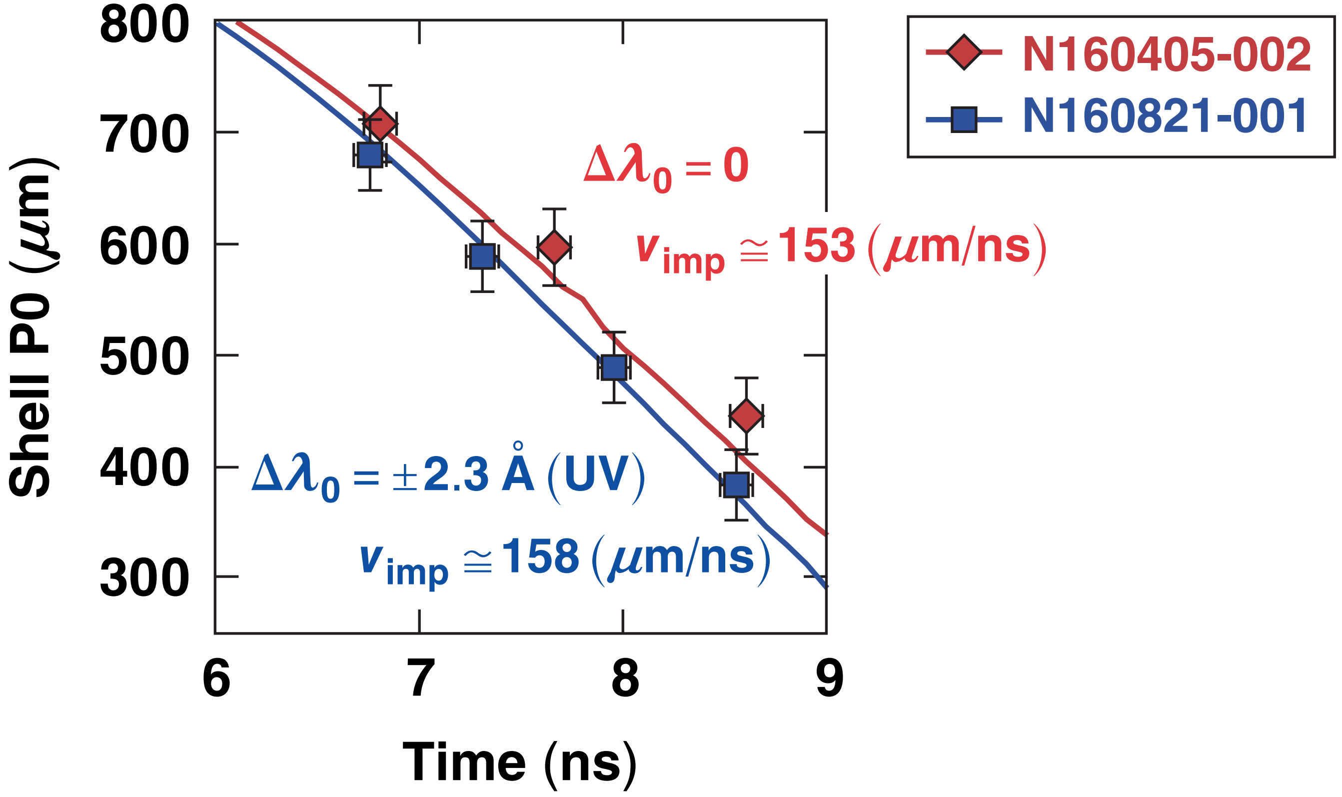




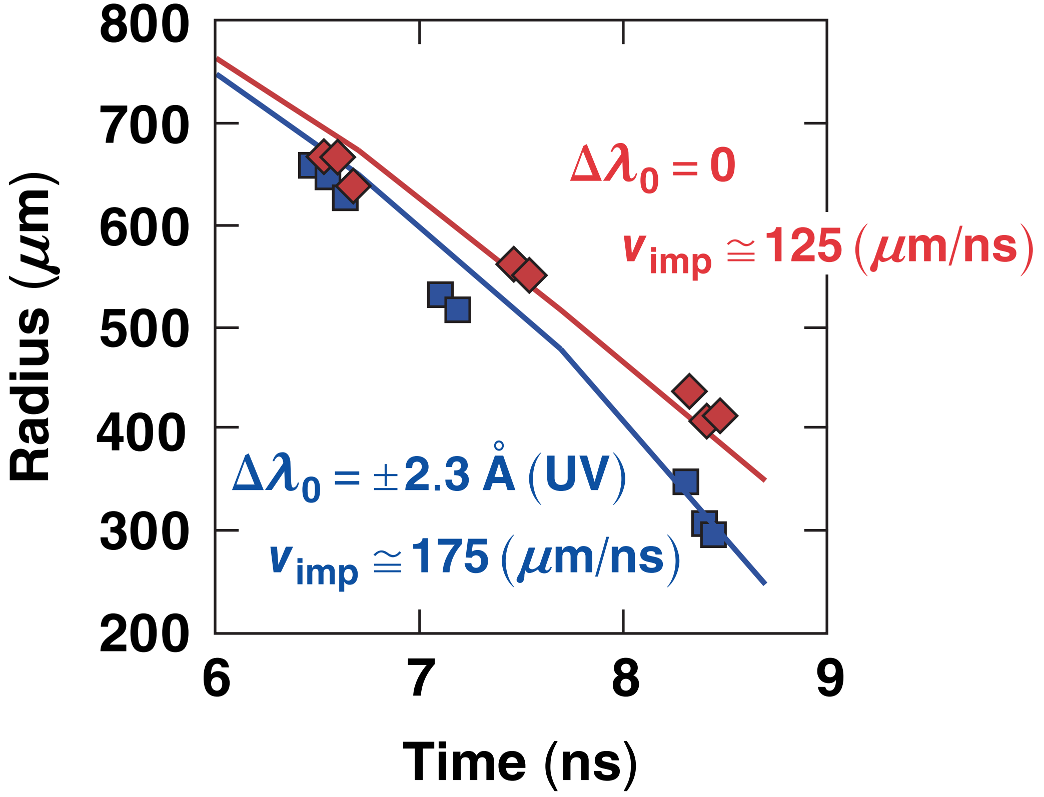
Only $\Delta\lambda_0$ was changed.

Increased absorption by means of wavelength detuning enhances the equatorial shell trajectory as predicted

Backlit average shell-radius simulation versus measurement

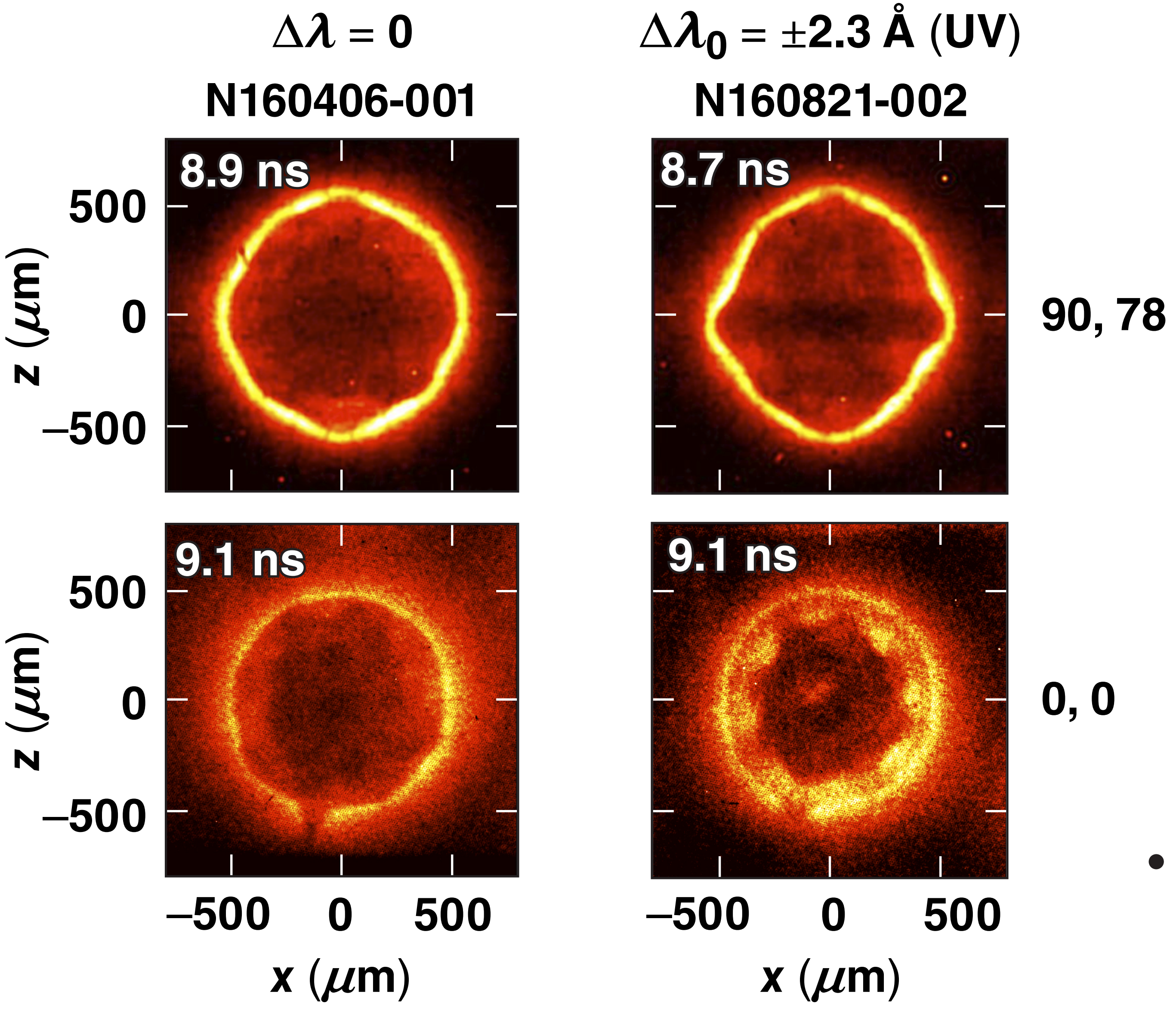


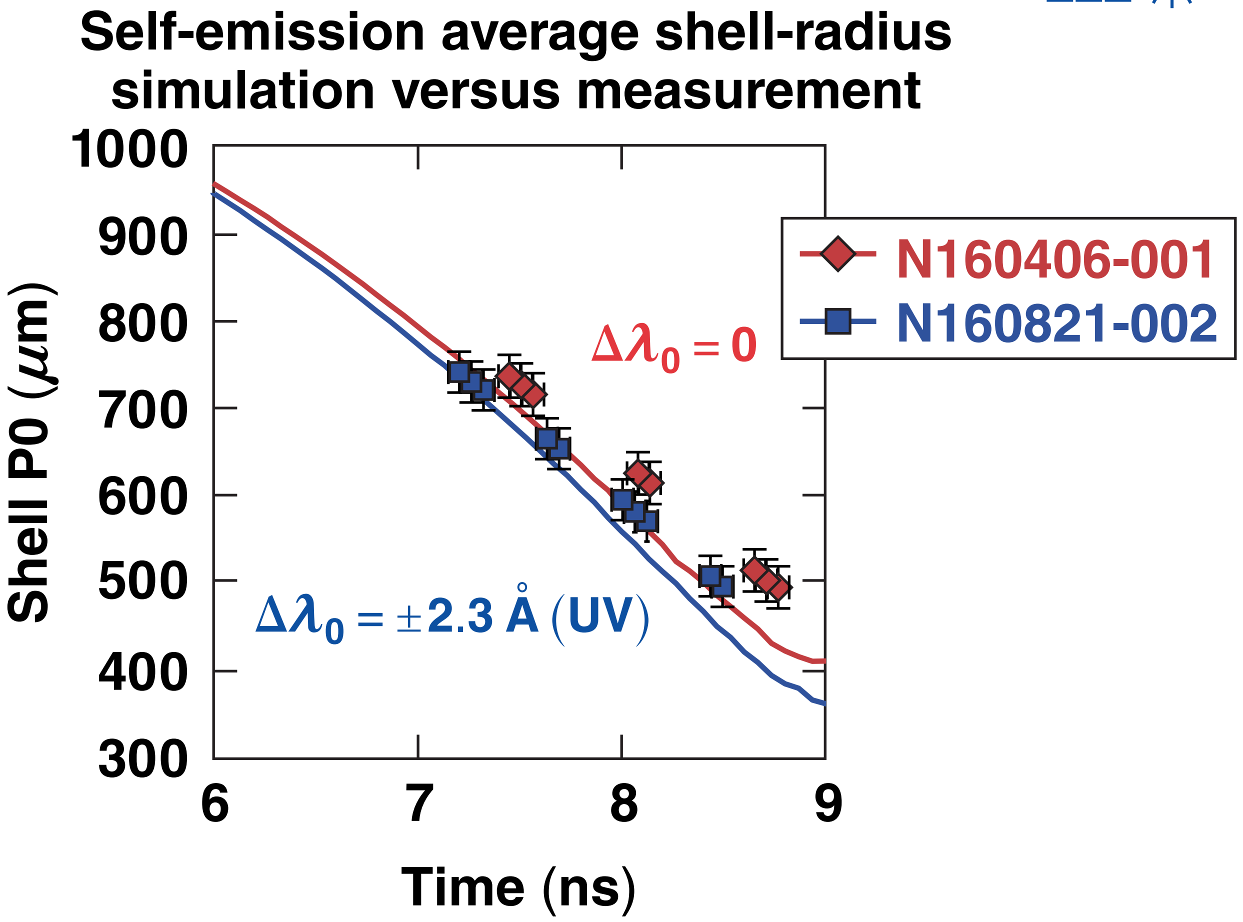
Backlit equatorial shell-radius simulation versus measurement



TC13198

Measured self-emission images show similar morphology and late-time higher compression effects



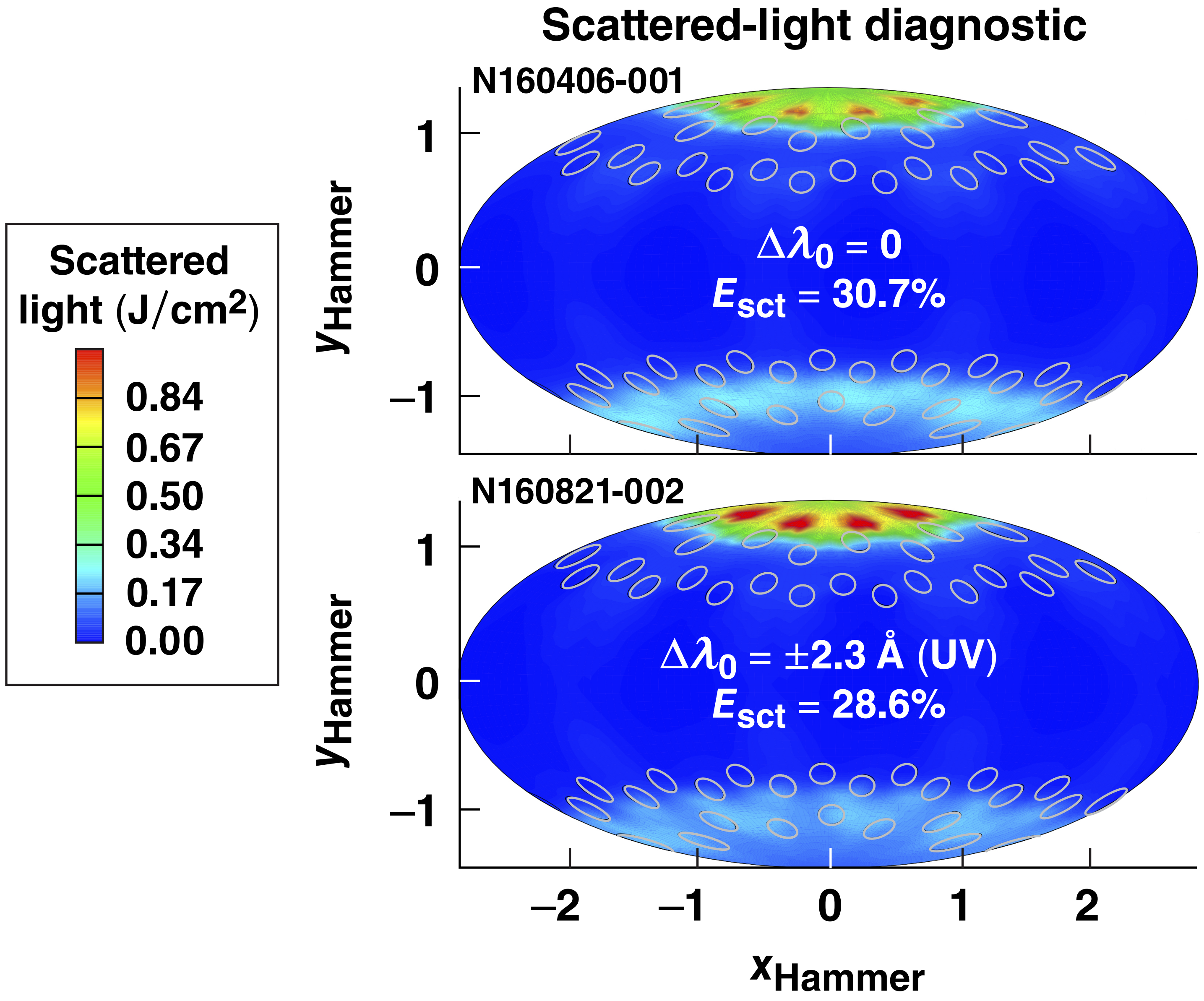


- Similar trend as backlit images
  - deviation from simulation attributed to imprint*

*P. B. Radha *et al*., Phys. Plasmas 23, 056305 (2016).

TC13199

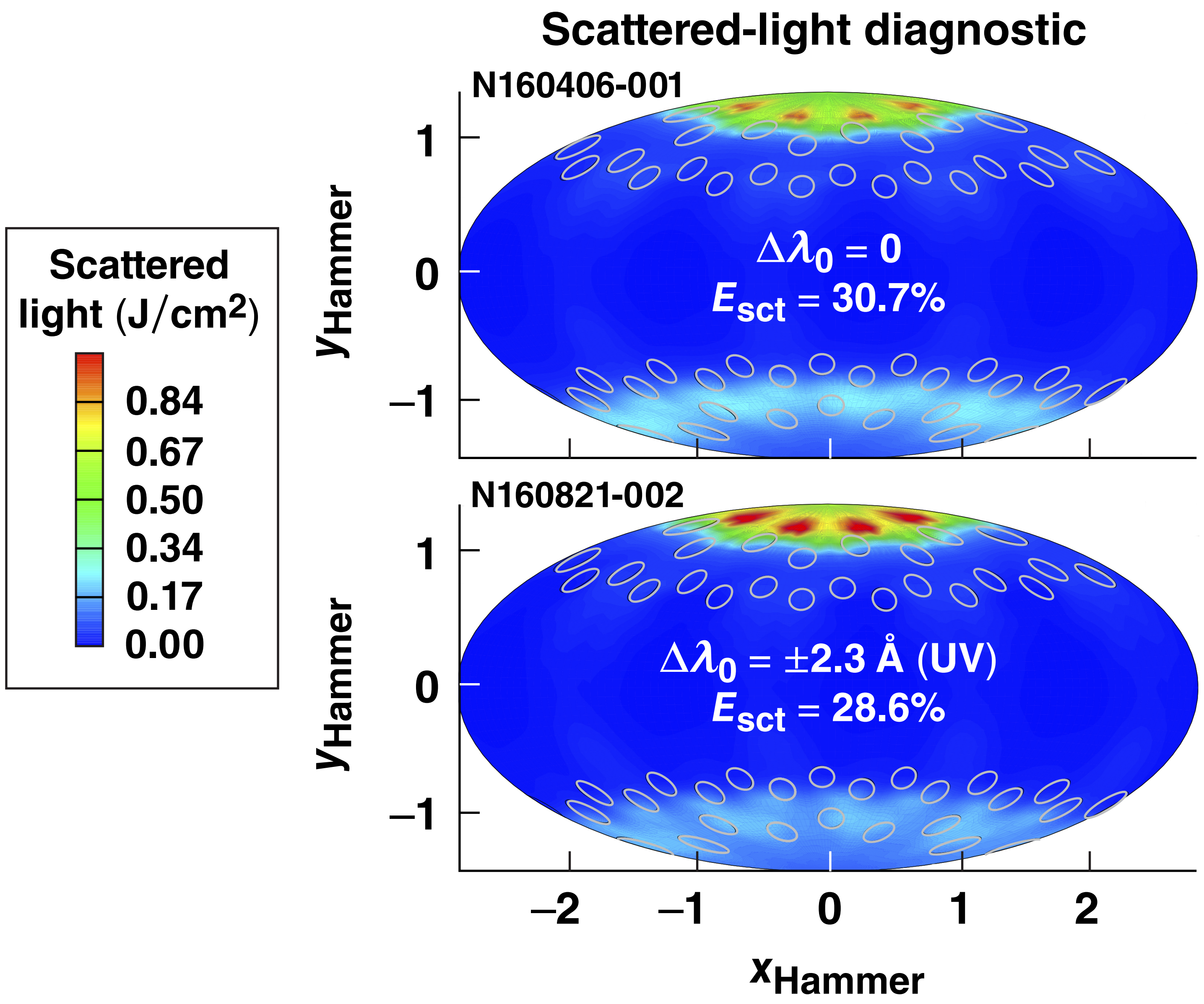
Hemispheric wavelength detuning mitigates CBET and consequently reduces scattered light

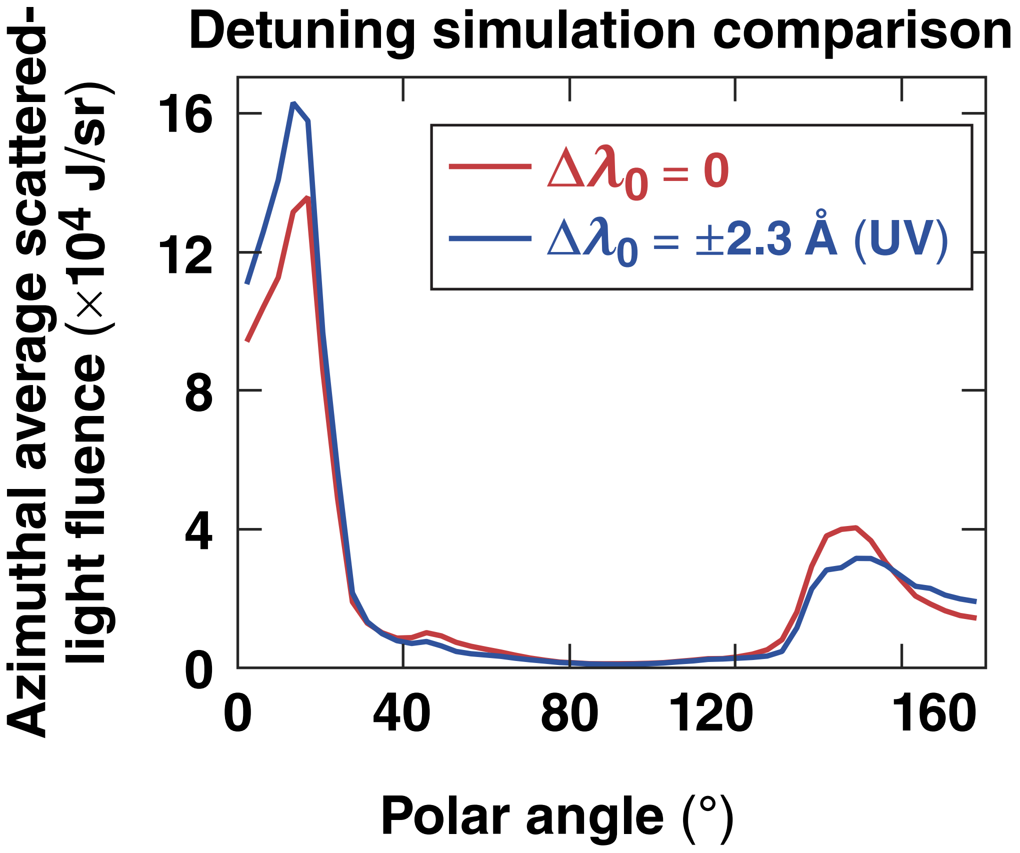


- The scattered light is asymmetric because of the single hemisphere cone swapping; causes larger spots to be repointed to the equator in the southern hemisphere
- The northern pole brightens with active $\Delta\lambda_0$, indicating the higher compression plus non-optimal spot shapes (no SMA)
- The scattered light is reduced with active $\Delta\lambda_0$, especially in the southern hemisphere

TC13038b

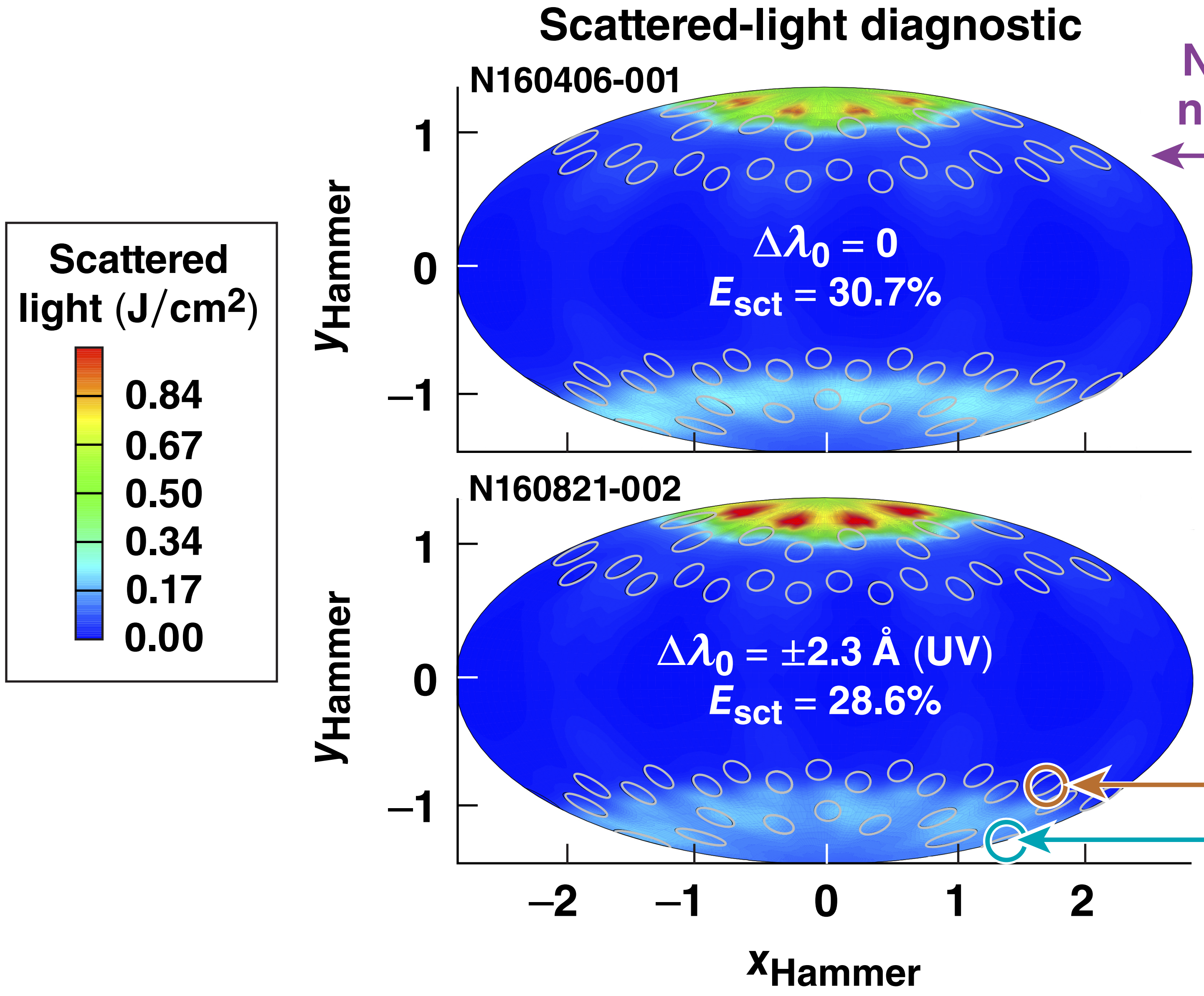
Hemispheric wavelength detuning mitigates CBET and consequently reduces scattered light

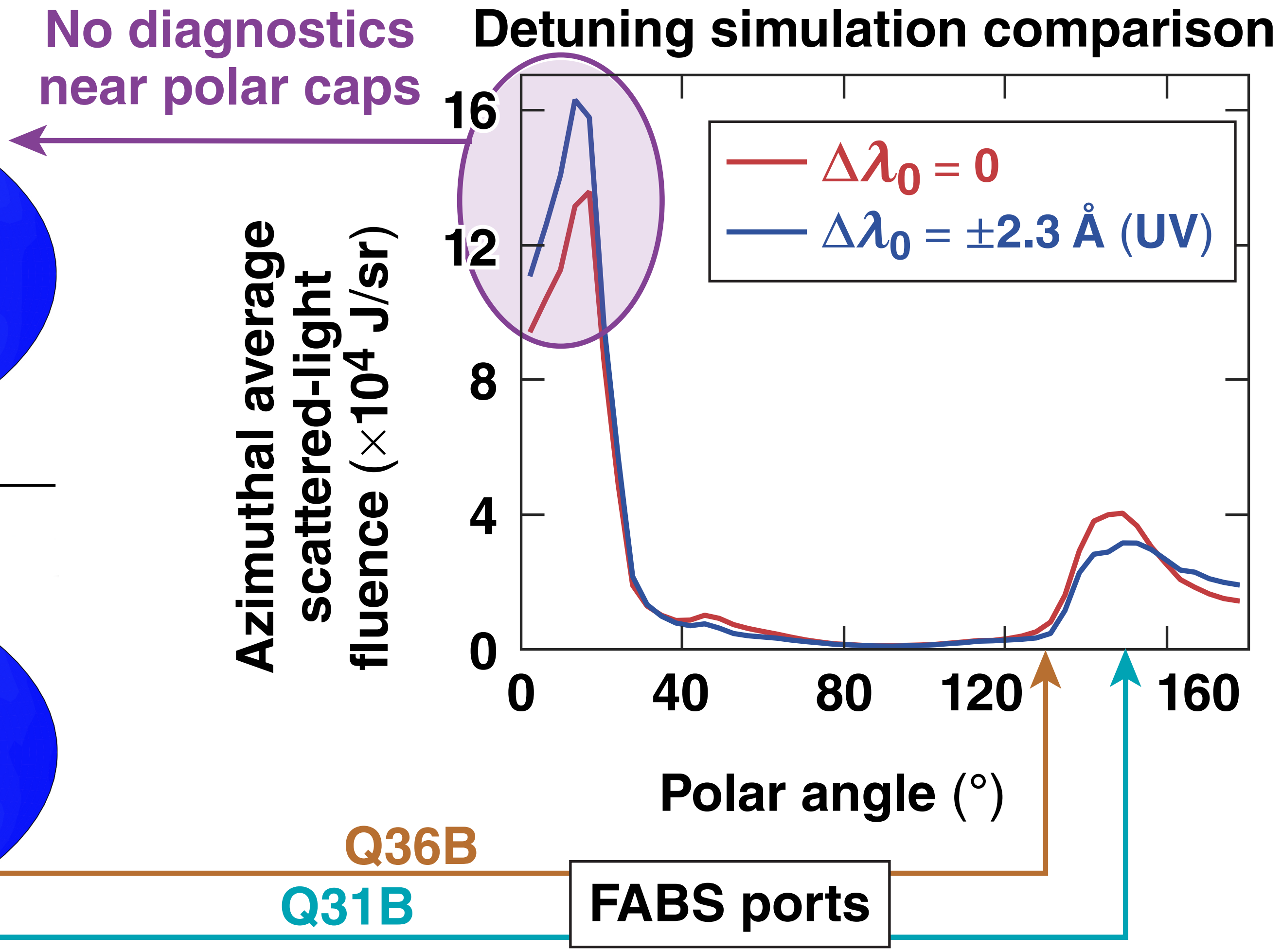




TC13038c

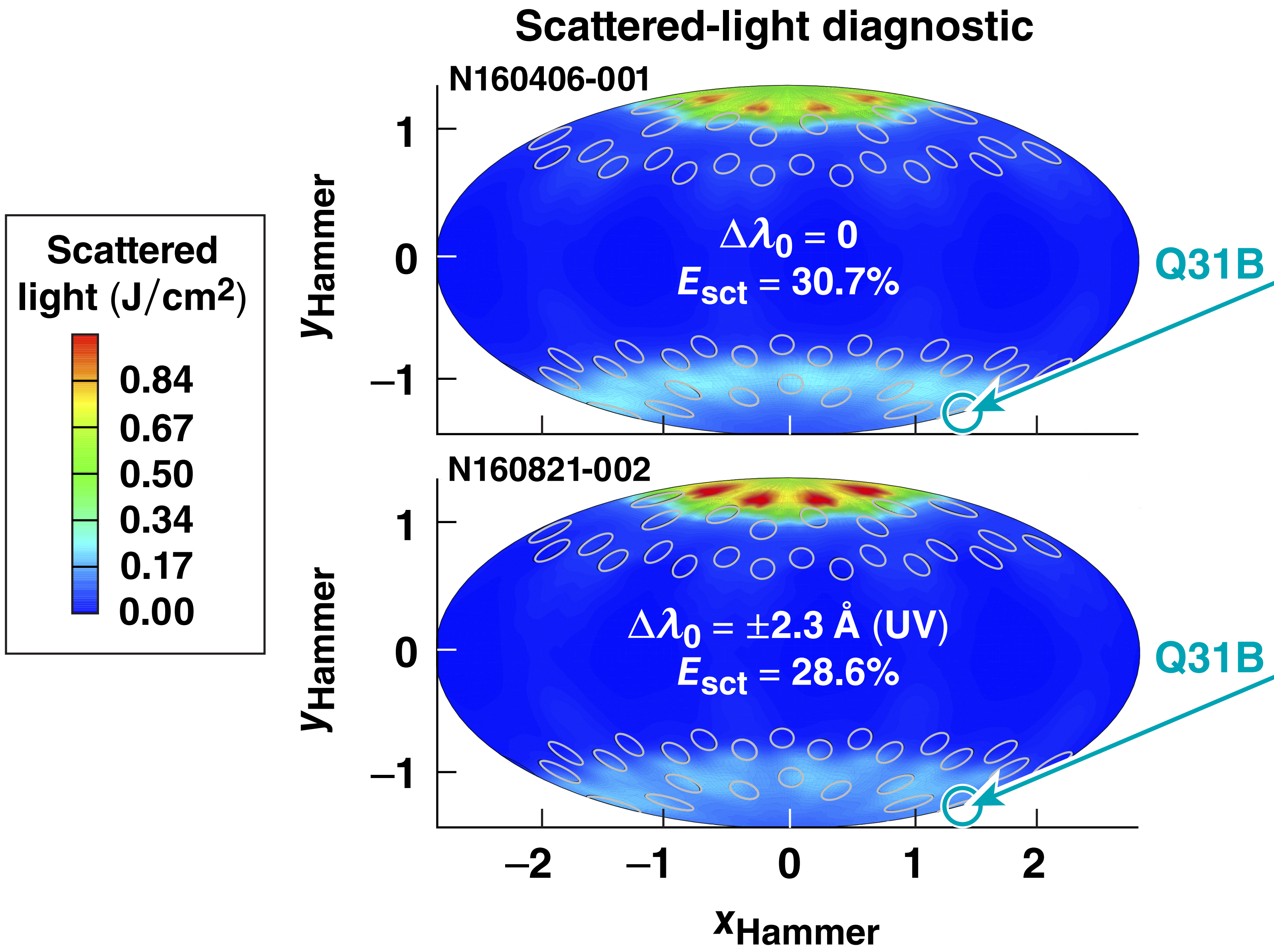
Hemispheric wavelength detuning mitigates CBET and consequently reduces scattered light

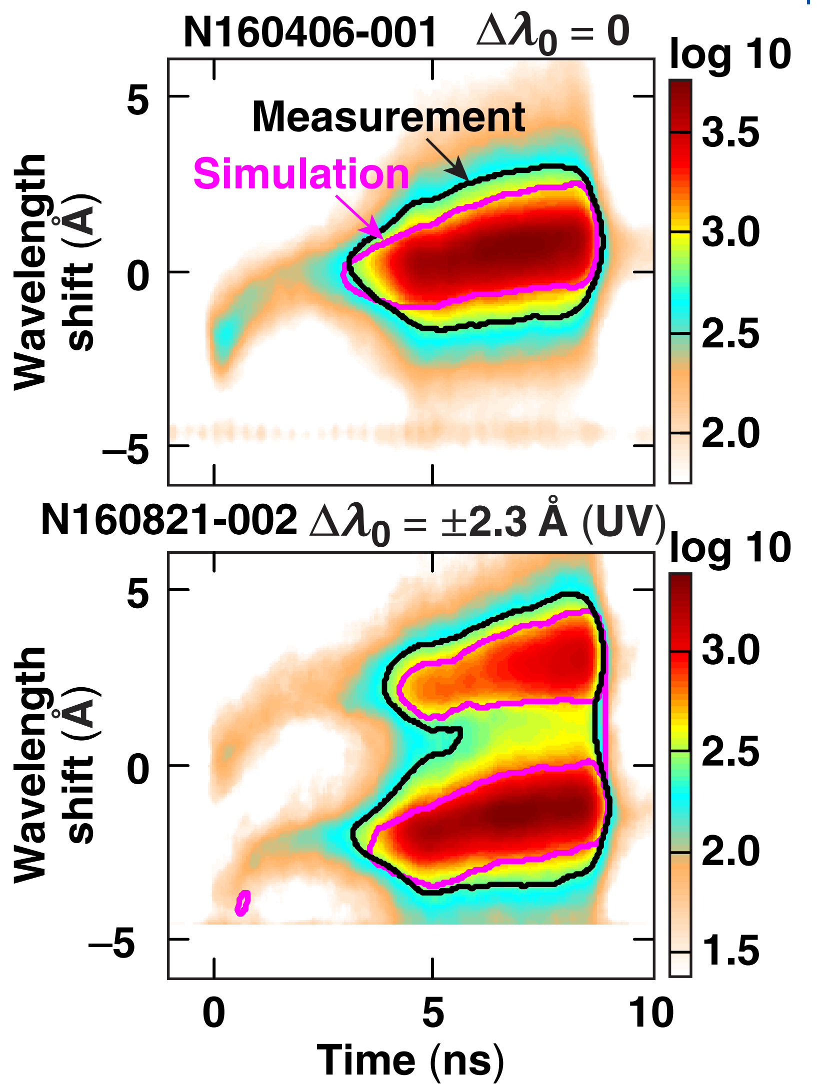




TC13038d

Measured and simulated chirped-scattered-light data are in good agreement and show decreased scattered light for active detuning





- Contours are at 10% of peak for measurement and simulation

TC13038e

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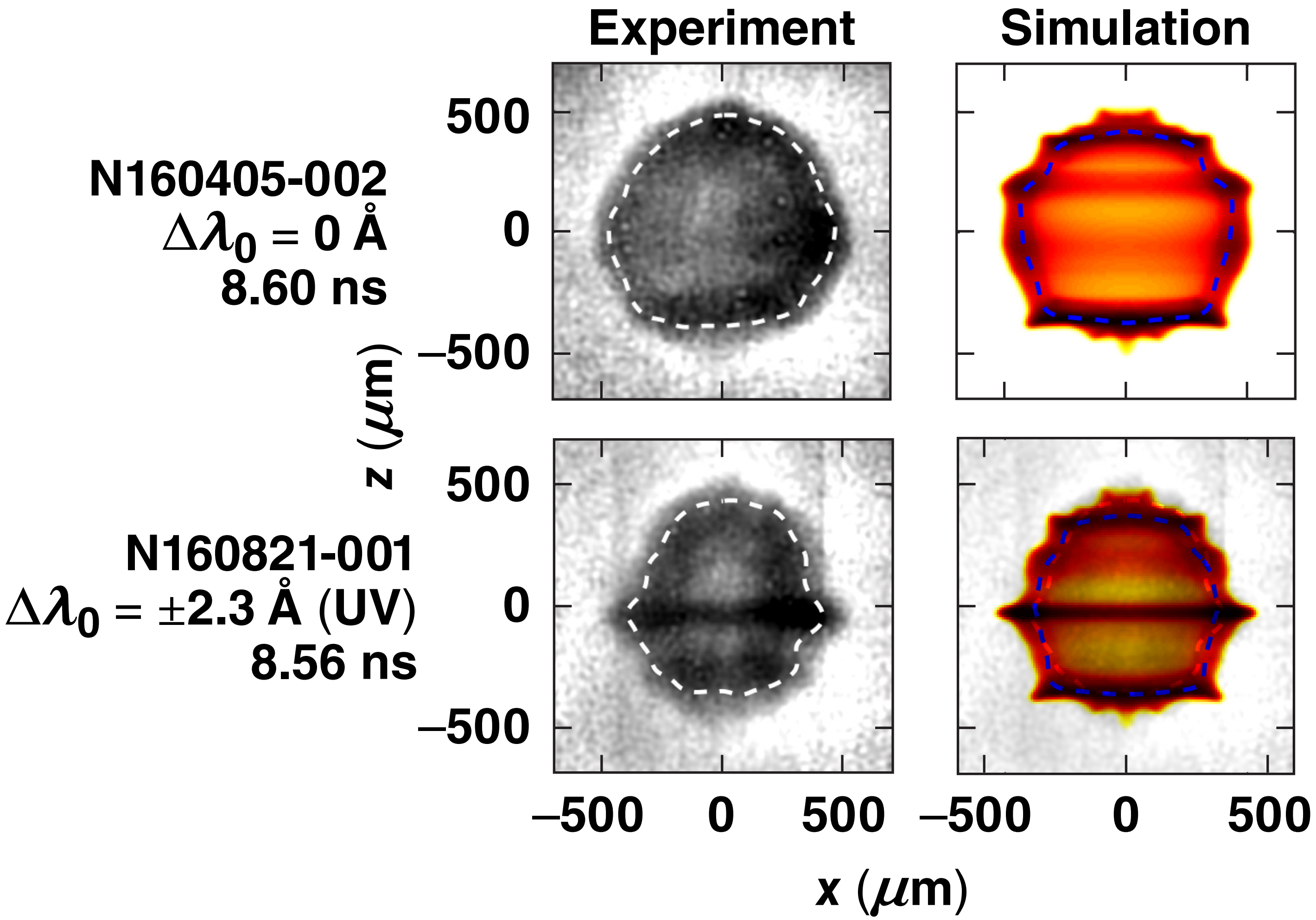
  - **e.g., the predicted equatorial mass accumulation was observed, which is a by-product of efficient equatorial drive with non-optimal spot shapes and a nearly "round" shell in PDD**
- **The successful NIF wavelength-detuning experiments lay the foundation for future advances: larger $\Delta\lambda_0$, multiple wavelengths, flexible wavelength distribution, optimized spot shapes, etc.**

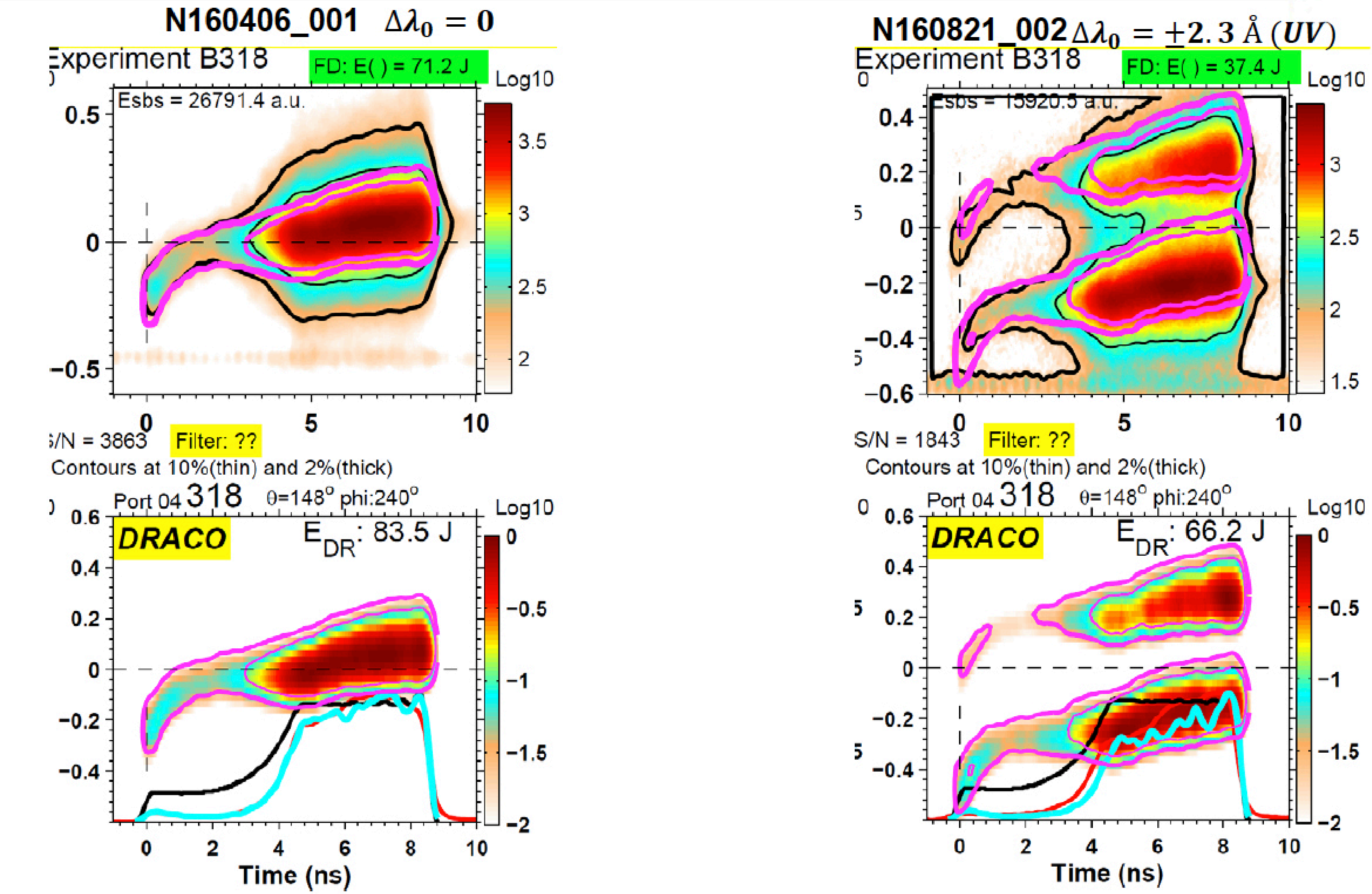
Backup

Wavelength-detuning CBET mitigation for polar and symmetric direct drive



U2043a

Measured and simulated chirped-scattered-light data are in good agreement and show decreased scattered light for active detuning



Note: some diagnostic ports show some anomalies that are under investigation

TC13200

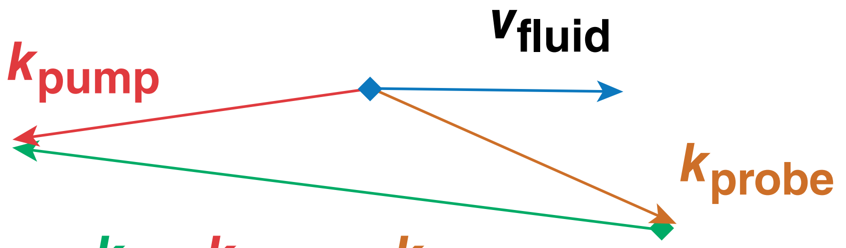
Laser-energy coupling loss caused by CBET can be mitigated in different domains that can be combined

- Spatial domain (reduction of the interaction volume)
  - dynamic spot-shape changes; "zooming"
    - reduces on-target energy, induces long-wavelength nonuniformity, and increases imprint
  - spot-shape apodization
    - static spot-shape design tailored to the target
    - use optimal super-Gaussian shape while not altering imprint
- Spectral domain (wavelength detuning)
  - detuning shifts resonances into lower interaction volumes
  - does not induce spot-shape distortion or imprint
  - all required technologies exist, i.e., no R&D; low risk
  - will cause system-wide optics upgrades and downtime; high cost
  - detuning is more effective in PDD
- Temporal domain
  - time multiplexed pulses reduce interaction-time overlap
  - requires short pulses to minimize affect on hydrodynamics
  - causes increased peak power

TC12956

The interaction of crossed laser beams within an expanding plasma causes CBET between beams

- This stimulated Brillouin scattering (SBS)-based interaction leads to a resonance condition for transferring energy between a pump ray and a probe ray by means of an ion-acoustic wave k_a*



$$k_a = k_{pump} - k_{probe}$$

- The resonance condition peaks when the matching condition is met

$$\eta = \frac{(\omega_{pump} - \omega_{probe}) - k_a \cdot v_{fluid}}{|k_a| c_a}$$

$$\begin{cases} \eta > 0; \text{gain} \\ \eta < 0; \text{loss} \end{cases}$$

*C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).

The CBET effect is modeled by generalizing collinear interacting plane waves to include arbitrary incidence angles and polarization*

- The exponential CBET gain or loss factor is given by

$$d\tau_{XBT} = \zeta_{pol} \left[\frac{e^2}{c^3 m_e} \frac{n'_e}{1-n'_e} \frac{\lambda_0 \langle Z \rangle}{\langle Z \rangle T_e + 3T_i} \right] \underbrace{P(\eta)\, I_{pump}}_{\text{ASR}} ds$$

$$P(\eta) = \frac{\eta \nu_a}{(\eta \nu_a)^2 + (1-\eta^2)^2}$$

Resonance function;**
$P = \pm 1/\nu_a$, when matched; i.e., $\eta = \pm 1$

$$\eta = \frac{(\omega_{pump} - \omega_{probe}) - k_a \cdot v_{fluid}}{|k_a| c_a}$$

Matching condition
$\begin{cases} \eta > 0; \text{gain} \\ \eta < 0; \text{loss} \end{cases}$

- Random polarization ζ_{pol} is included using either a constant 1/2 factor or $1/4 \left\{ 1 + \left[\hat{k}_{pump} \cdot \hat{k}_{probe} \right]^2 \right\}$***
- Probe energy is gained or lost as $E_0 \left[e^{d\tau_{IBS^\dagger}} e^{d\tau_{CBET}} - 1 \right]$ in a cell

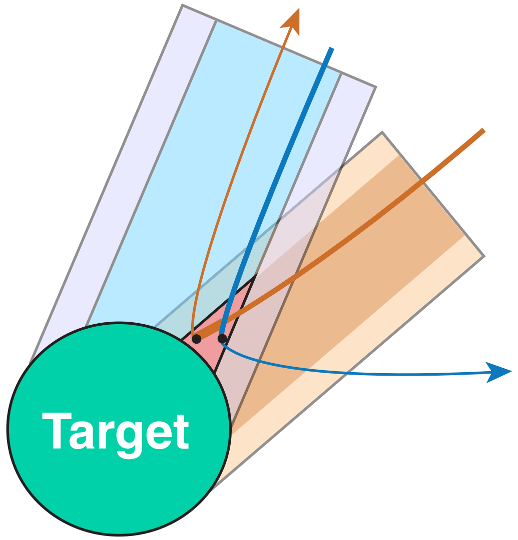
*C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).
**ASR = angular-spectrum representation
***P. Michel, LLE/LLNL Meeting (May 2014).
†IBS = inverse bremsstrahlung

TC11307b

The CBET interactions can be grouped roughly into two modes

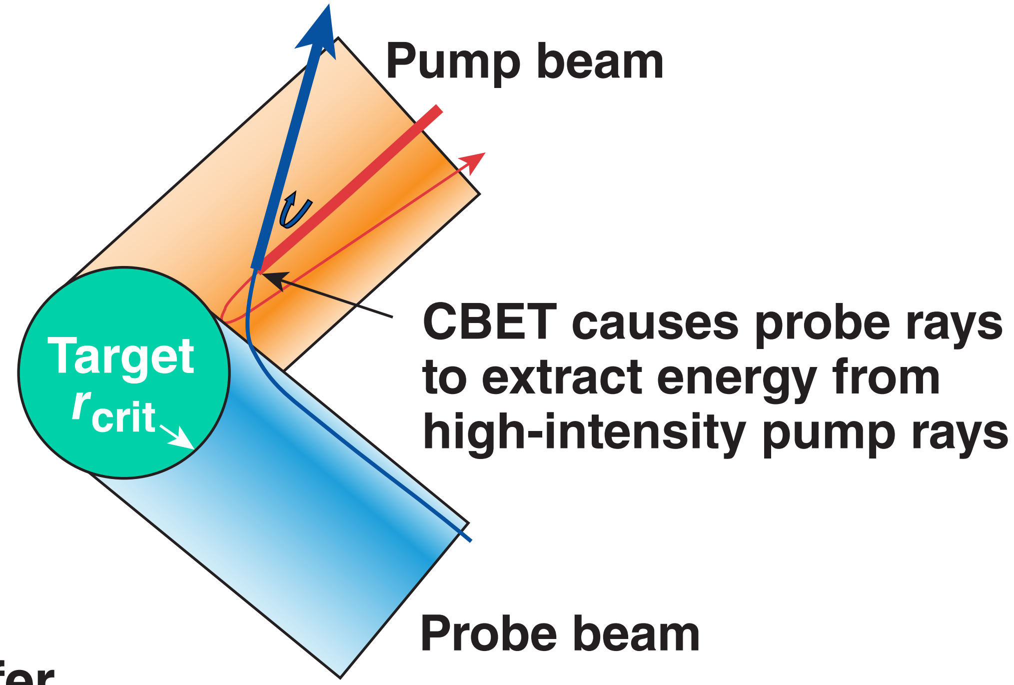
- The laser-beam interaction for directly driven targets (symmetric or PDD) covers a wide variety of angles, frequencies, and directions
  - refraction, chirping, and multibeam geometry are responsible

Sidescatter mode



- Similar to the ring energy transfer used for NIF indirect-drive ignition (IDI)
- Has minimal impact on absorption

Backscatter mode



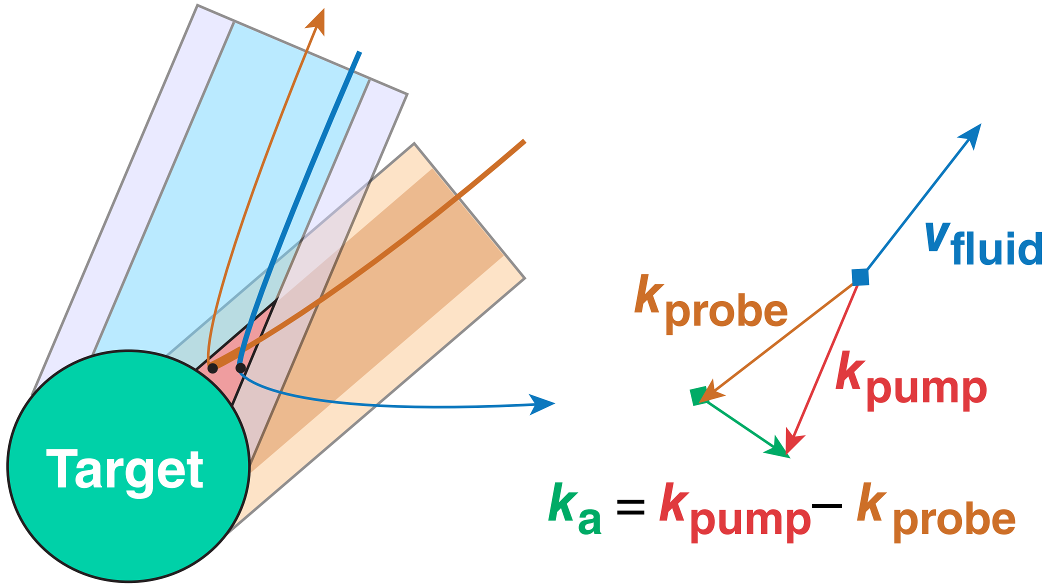
- The primary CBET mode that reduces energy absorption

TC11305e

The sidescatter mode causes an inbound beam-to-beam CBET exchange

- The sidescatter mode occurs when both beams are inbound or outbound

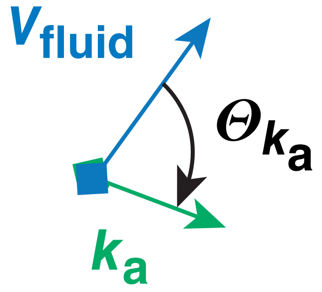
Sidescatter mode



Matching condition

$$\Delta\omega = \omega_{pump} - \omega_{probe} = |k_a| c_a + k_a \cdot V_{fluid}$$

$$\lim_{V_{fluid} \to Mc_a \hat{r}} \Rightarrow \eta = \frac{\Delta\omega - |k_a| c_a M \cos\theta_{k_a}}{|k_a| c_a}$$

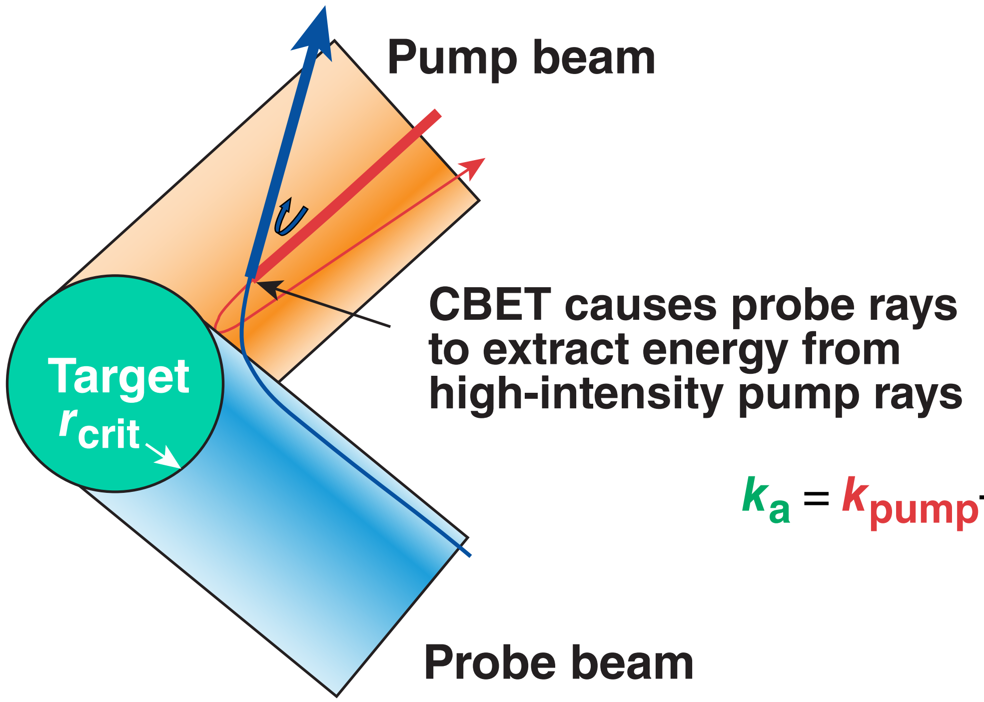


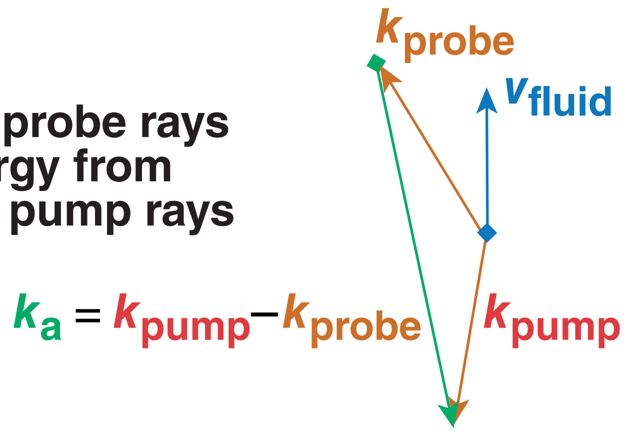
- The resonance condition still peaks where the fluid is supersonic (small $\Delta\omega$)
- The $|k_a|$ is much smaller, however, and the angle θ_{k_a} can be near orthogonal, which implies that the $k_a \cdot V_{fluid}$ term no longer dominates
  - the sign of the $\Delta\omega$ can now determine gain/loss for smaller values

The backscatter mode dominates the CBET loss for directly driven targets

- The backscatter mode occurs for opposing beams

Backscatter mode

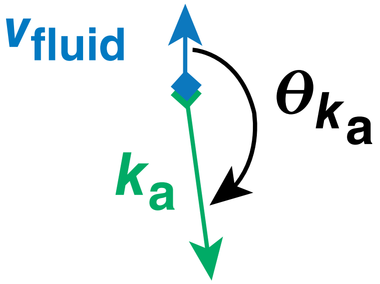




Matching condition

$$\Delta\omega = \omega_{pump} - \omega_{probe} = |k_a| c_a + k_a \cdot V_{fluid}$$

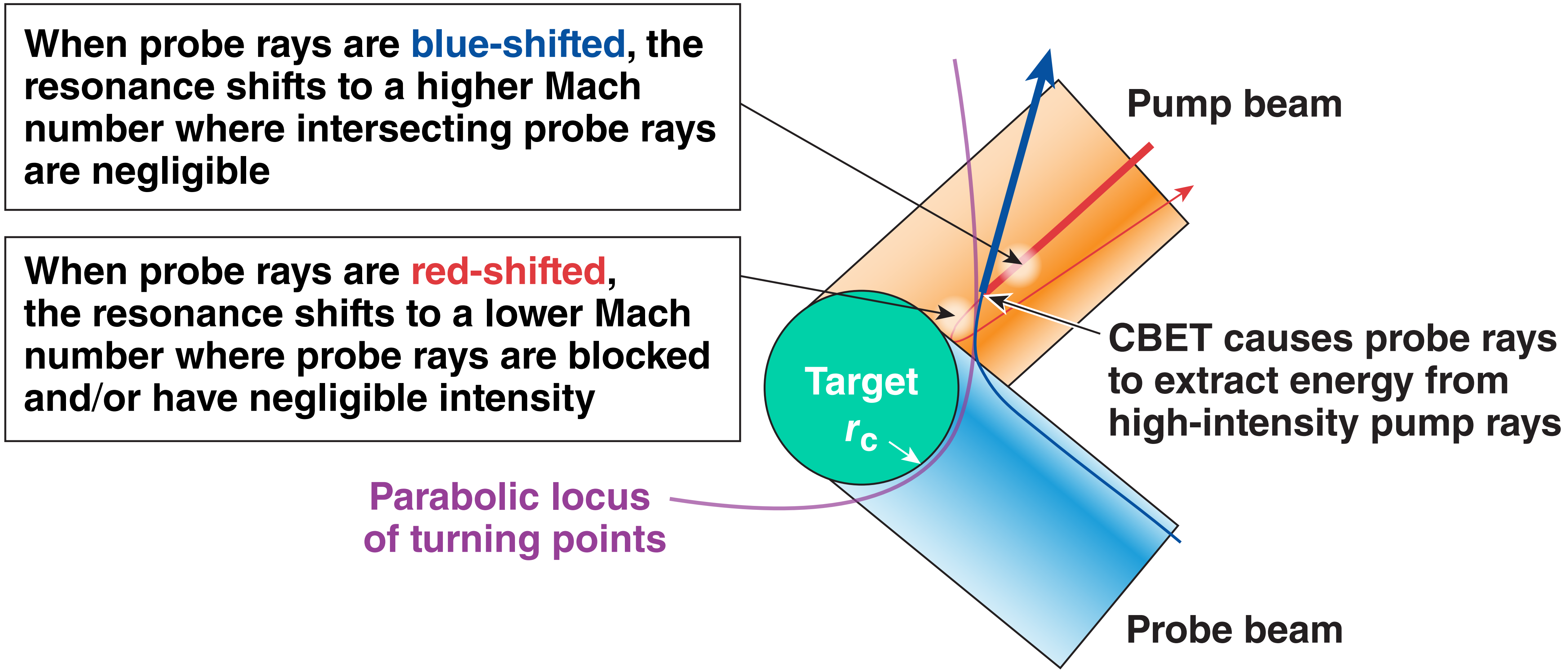
$$\lim_{V_{fluid} \to M c_a \hat{r}} \Rightarrow \eta = \frac{\Delta\omega - |k_a| c_a M\cos\theta_{k_a}}{|k_a| c_a}$$



- The resonance condition peaks where the fluid is supersonic (small $\Delta\omega$)
- As the frequency difference increases, the resonance condition shifts to lower/higher sonic speeds depending on the sign (e.g., $M = \{0.4, 1.6\}$ for ±6-Å UV)
  - dominated by the $k_a \cdot V_{fluid}$ term; its sign determines whether there is gain/loss
  - frequency difference cannot alter the gain/loss unless it can counter the large $k_a \cdot V_{fluid}$ term (e.g., ±20-Å UV)

TC11366b

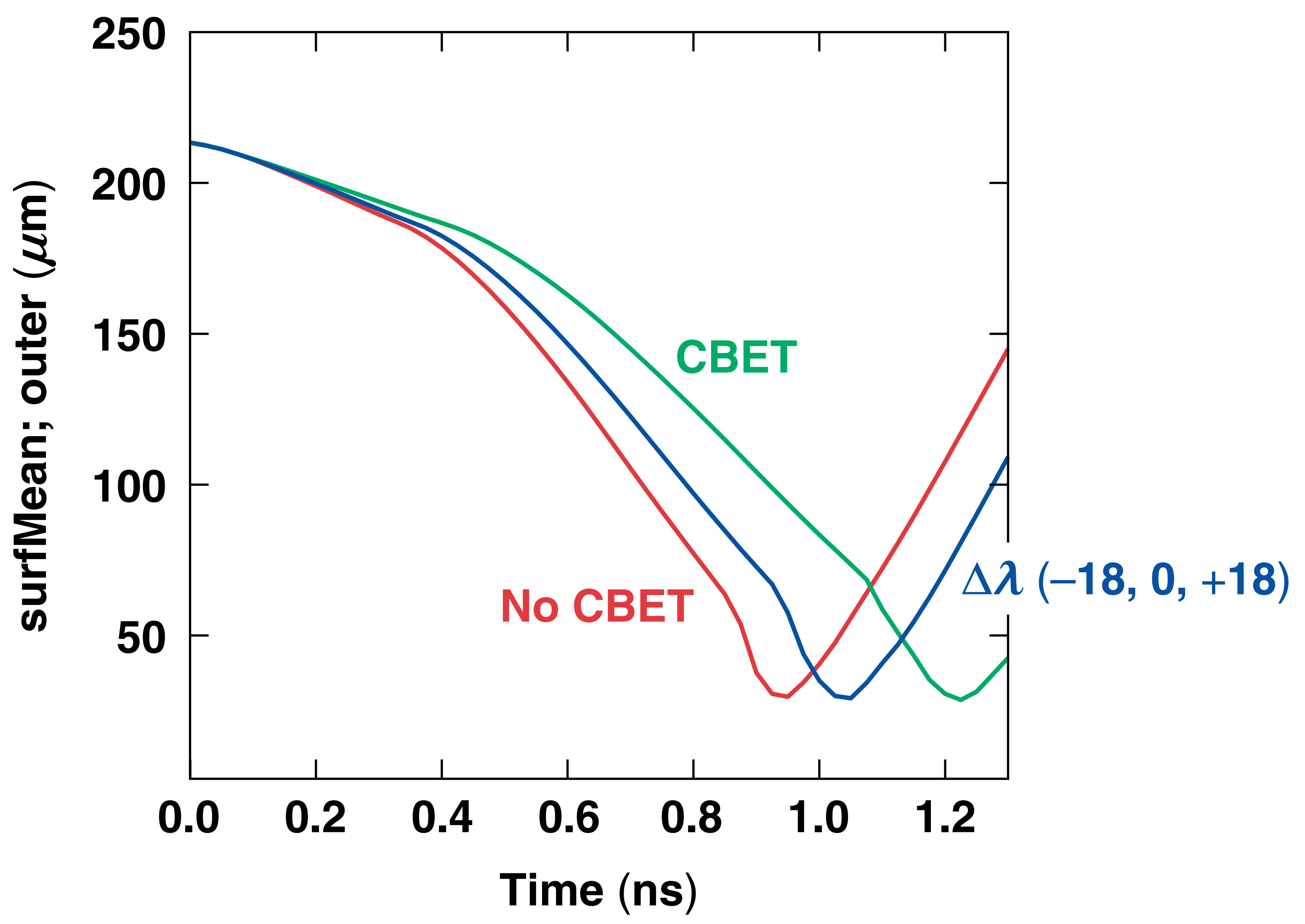
Successful wavelength detuning shifts the resonance location sufficiently to mitigate CBET



- The magnitude of $\Delta\lambda_0$ determines the mitigation duration
  - works for both symmetric and PDD
  - tailoring the spot shape will help limit the required $\Delta\lambda_0$

TC11766f

The simulated shell trajectories indicate measurable differences detectable with the gated x-ray framing camera



- At 900 ps, the shell radius is 32 μm smaller for wavelength detuning

TC12963