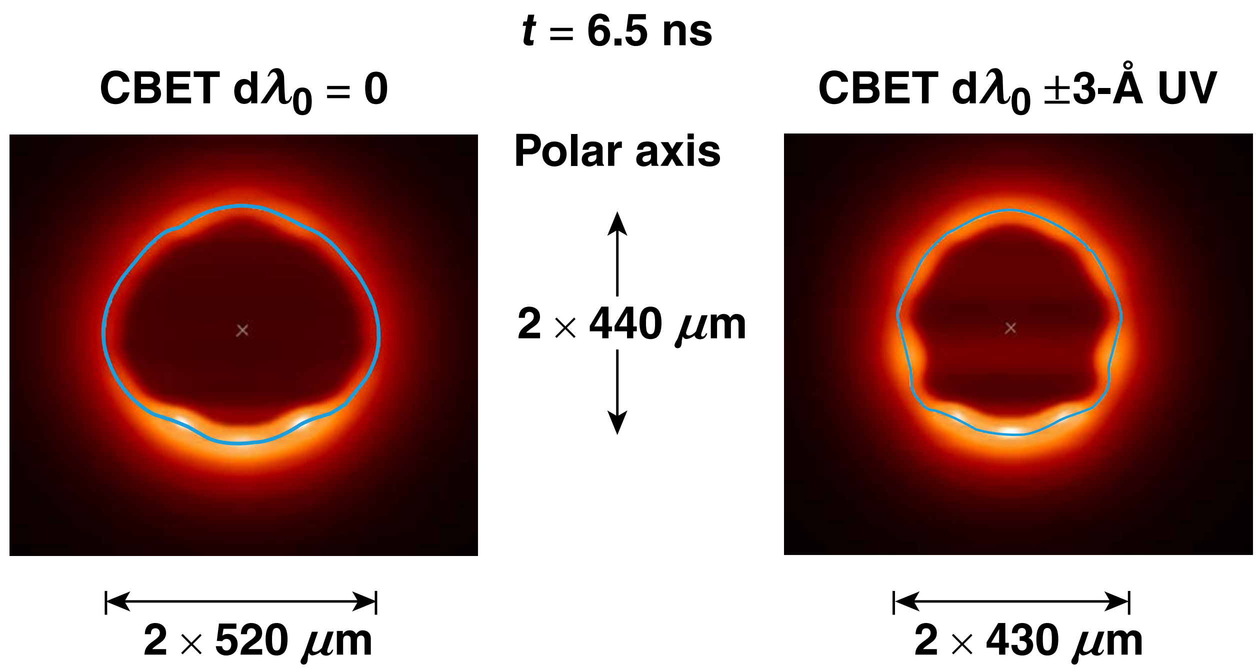
Cross-Beam Energy Transfer Mitigation Strategy for NIF Polar Drive



Wavelength detuning using the National Ignition Facility's (NIF's) current configuration.

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Summary

Simulations indicate that wavelength detuning is a promising cross-beam energy transfer (CBET) mitigation scheme achievable at the National Ignition Facility (NIF)

- The CBET effect increases scattered light through the stimulated Brillouin scattering (SBS) of outgoing rays that removes energy from incoming high-energy rays
- The wavelength detuning and initial spot-shape mitigation schemes work together with pulse modification to offer a potential point design for polar drive (PD) at the NIF
- The current NIF configuration allows for initial testing of the wavelength mitigation scheme

Collaborators

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Outline

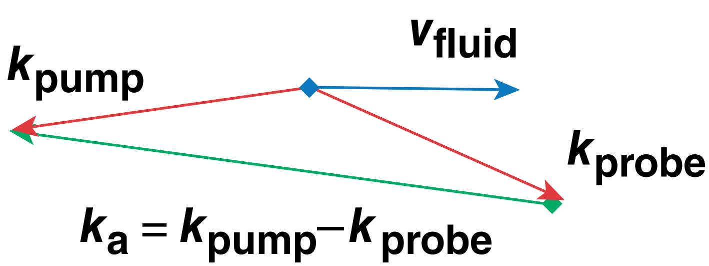
CBET mitigation strategy for NIF polar drive

UR LLE

- **CBET overview**
- Modeling CBET
- Effects of CBET
- Comparison to NIF experimental results
- CBET mitigation schemes
- Effects of $d\lambda_0$
- Employ hemispheric $d\lambda_0$
- Employ $d\lambda_0$ on the current NIF configuration

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

- This SBS-based interaction leads to a resonance condition for transferring energy between a pump ray and a probe ray via an ion-acoustic wave k_a*



- The resonance condition peaks when the matching condition is met

$$\eta = \frac{(\omega_{pump} - \omega_{probe}) - k_a \cdot v_{fluid}}{|k_a| c_a} \quad \begin{cases} \eta > 0; \text{gain} \\ \eta < 0; \text{loss} \end{cases}$$

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

TC11306

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

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- The exponential CBET gain or loss factor is given by

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

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

Resonance function

Matching condition

$$\eta = \frac{(\omega_{\mathrm{pump}} - \omega_{\mathrm{probe}}) - k_a \cdot v_{\mathrm{fluid}}}{|k_a| c_a} \quad \begin{cases} \eta > 0; \text{gain} \\ \eta < 0; \text{loss} \end{cases}$$

- Random polarization ζ_{pol} is included using either a constant 1/2 factor or 1/4 $\left\{1 + \left[\hat{k}_{\mathrm{pump}} \cdot \hat{k}_{\mathrm{probe}}\right]^2\right\}$**

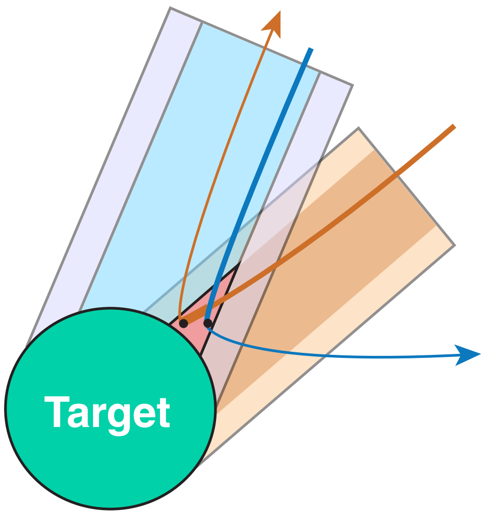
- Probe energy is gained or lost as $E_0 \left[e^{d\tau_{\mathrm{IBS}}} e^{d\tau_{\mathrm{XBT}}} - 1 \right]$ in a cell

*C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).
**G. Kerbel, P. Michel, and M. Marinak, LLNL White Paper, Lawrence Livermore National Laboratory, Livermore, CA (June 2011).

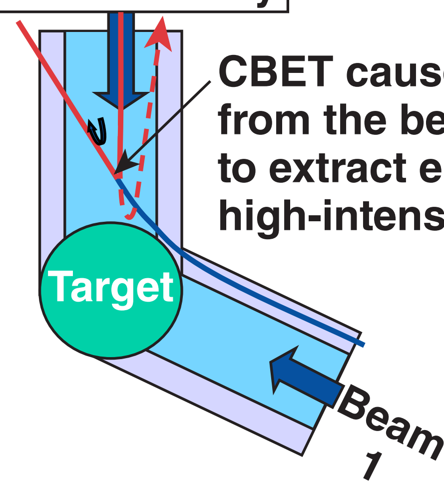
The CBET interactions can be grouped roughly into two modes

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

Sidescatter mode



Backscatter mode



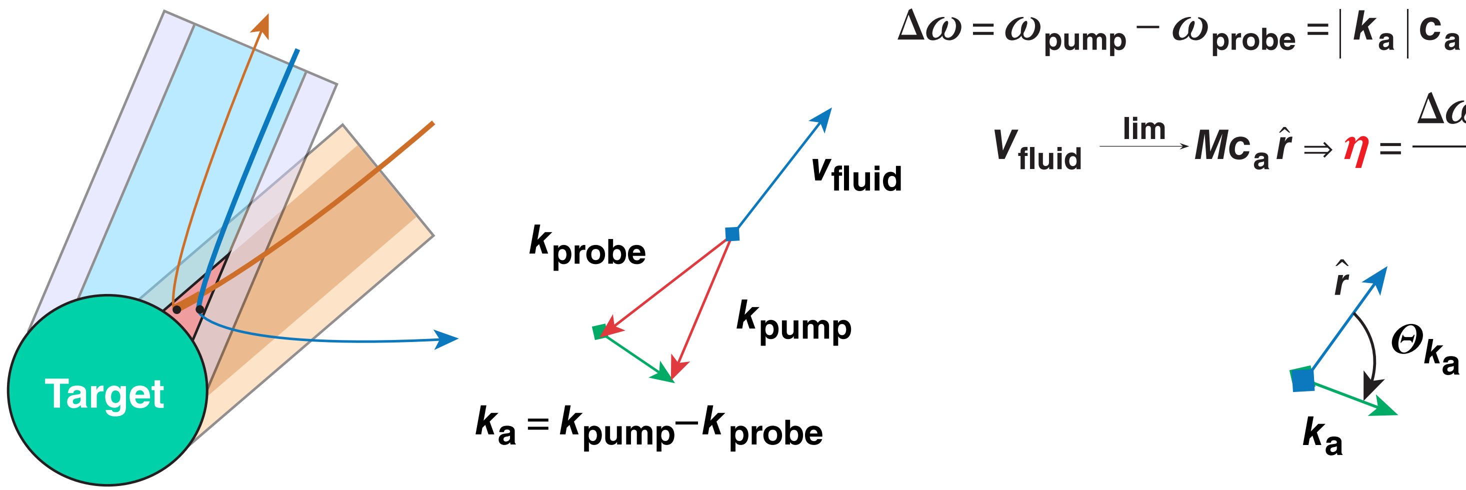
- Similar to the ring energy transfer used for NIF indirect drive (IDI)
- Has minimal impact on absorption

- The primary CBET mode that reduces energy absorption

TC11305

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

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



Matching conditions

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

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

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

TC11309

The backscatter mode dominates the CBET loss for directly driven targets

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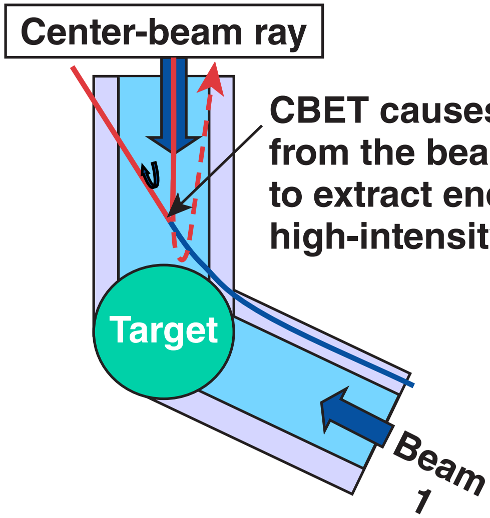
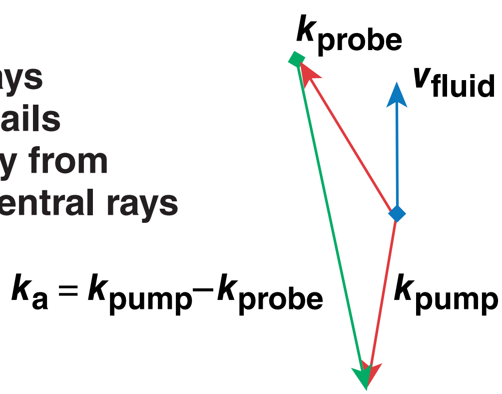
- The backscatter mode occurs for opposing beams





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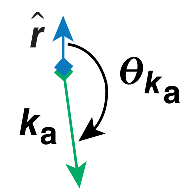

- The resonance condition still peaks where the fluid is supersonic (small $\Delta\omega$)
- As the frequency difference increases, the resonance condition shifts to lower/higher sonic speeds depending on the sign (e.g., $M = \{0.4, 1.6\}$ for ±6-Å UV)
  - dominated by the $k_a \cdot V_{fluid}$ term; 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)

TC11366

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The ray's intensity is calculated two ways

- The probe's local intensity is accurately calculated using the formulation from Born and Wolf, which only depends on the local density gradient and is immune to issues with the turning point (there are no caustics or foci)

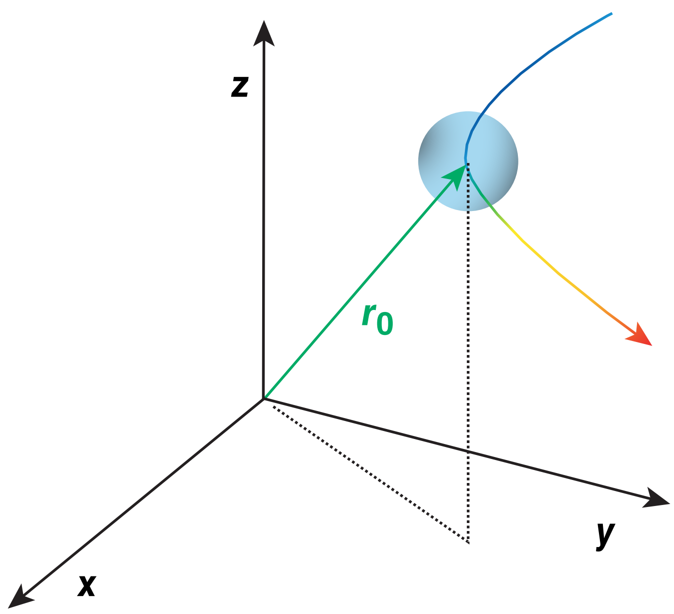
$$\frac{I_1}{I_2} = \frac{dS_2}{dS_1} = \frac{n_1}{n_2}\exp\left\{\int_{S_1}^{S_2} \frac{\nabla^2 \mathcal{J}}{n} ds\right\} = \frac{n_1}{n_2}\exp\left\{\int_{S_1}^{S_2} \frac{\nabla \cdot \{n\hat{s}\}}{n} ds\right\}$$

  - the probe's intensity is only required in the CBET fluid model with saturation

- The ASR intensity (pump) is a weighted accumulation of the natural ray quantity, viz. energy
  - rays do not carry intensity, they carry energy
  - the ASR accumulates the ray.energy*ray.pathlength product, which is then normalized to the cell's volume in a time step

CBET modeling (*Adaawam*) in the 2-D hydrodynamics code *DRACO* employs an ASR approach

- The ASR captures the accumulated weighted energy as a function of direction and color from all the beams that propagate through any cell



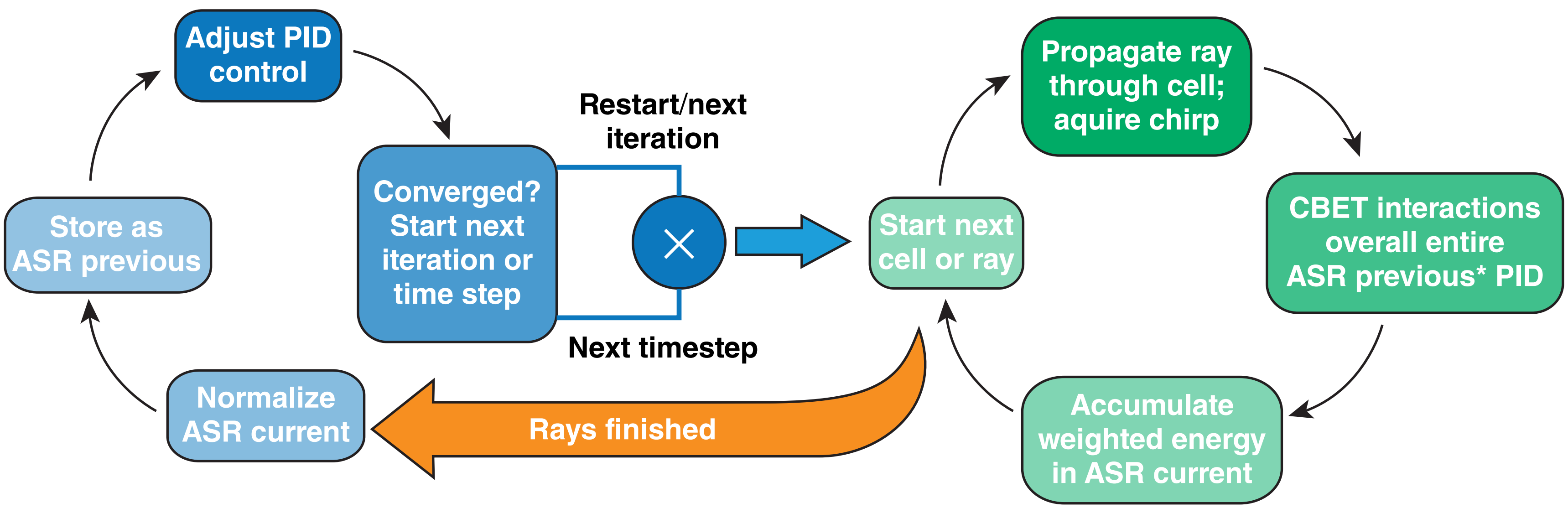
- r_0 is the ray's position vector within a cell
- Each cell collects the local ray direction using only two coordinates $\{\theta, \phi\}_{ray}$
- The local ray wavelength is collected as a separate dimension
- The ASR accumulates the ray's weighted energy (energy times the path length product) in each bin during an iteration

- The ASR is converted to intensity by normalizing to the volume times the time step size product for each cell after an iteration

TC11344

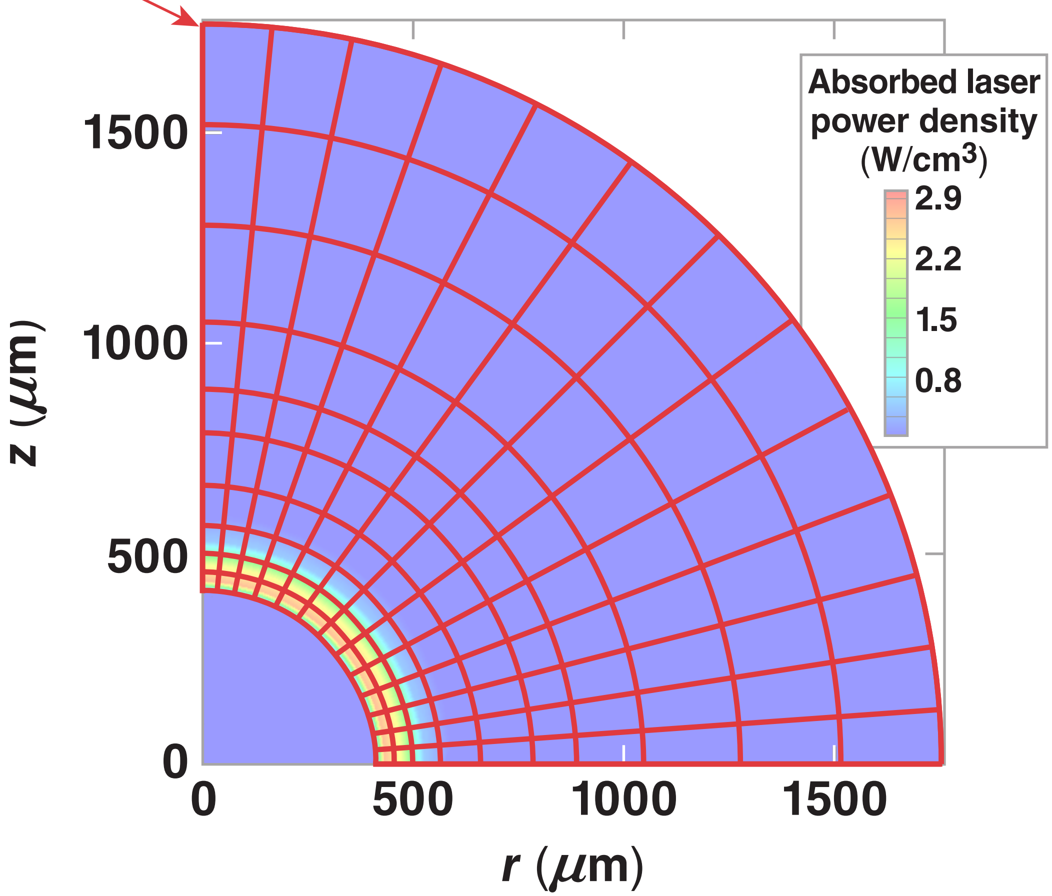
CBET modeling (*Adaawam*) in the 2-D hydrodynamics code *DRACO* uses feedback control to conserve energy

- Feedback through a PID-controller (proportional-integral-differential) loop provides vital control over CBET energy balance



- Feedback minimizes energy imbalance through a PID loop by adjusting the ASR until the adjustment returns to zero
  - energy is conserved by bringing all neighboring cells into equilibrium

Domain decomposition (*Daashkaa*) reduces the memory requirement by the number of cores used, allowing for even higher 3-D ASR resolution



- **Propagation region:** 150 × 350 = 52.5 kcells
- **3-D ASR:** 20^3 bins → 64 kB per cell
- **Memory for 3-D ASR:** 3.36 GB per core
  - single domain *DRACO* ray trace
- **Memory for 3-D ASR:** 26.3 MB per core
  - domain decomposed *DRACO* 3-D ray trace on 128 cores

TC9876a

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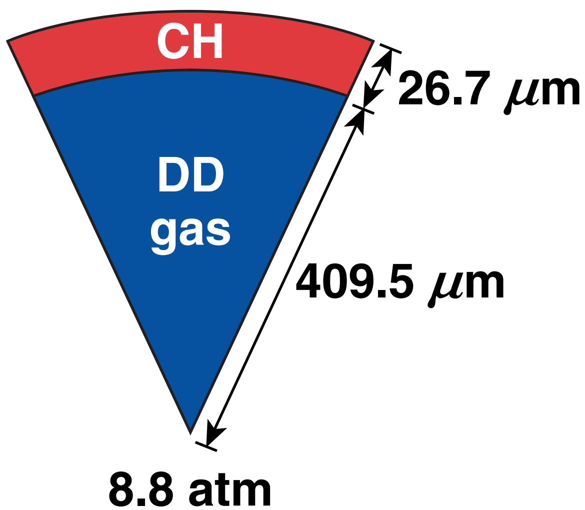
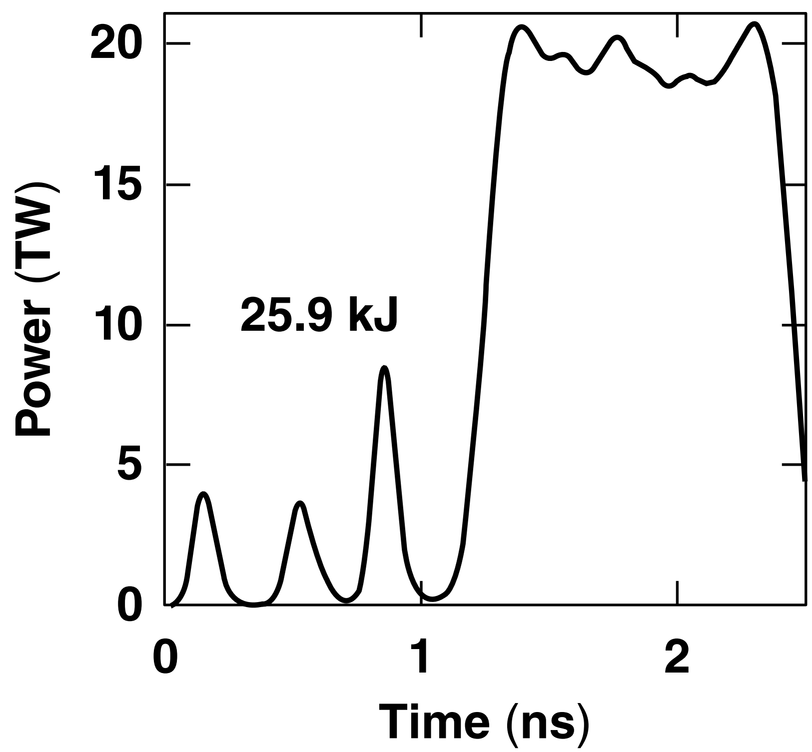
The symmetric-drive OMEGA shot 6000 is used to examine the basic CBET effect

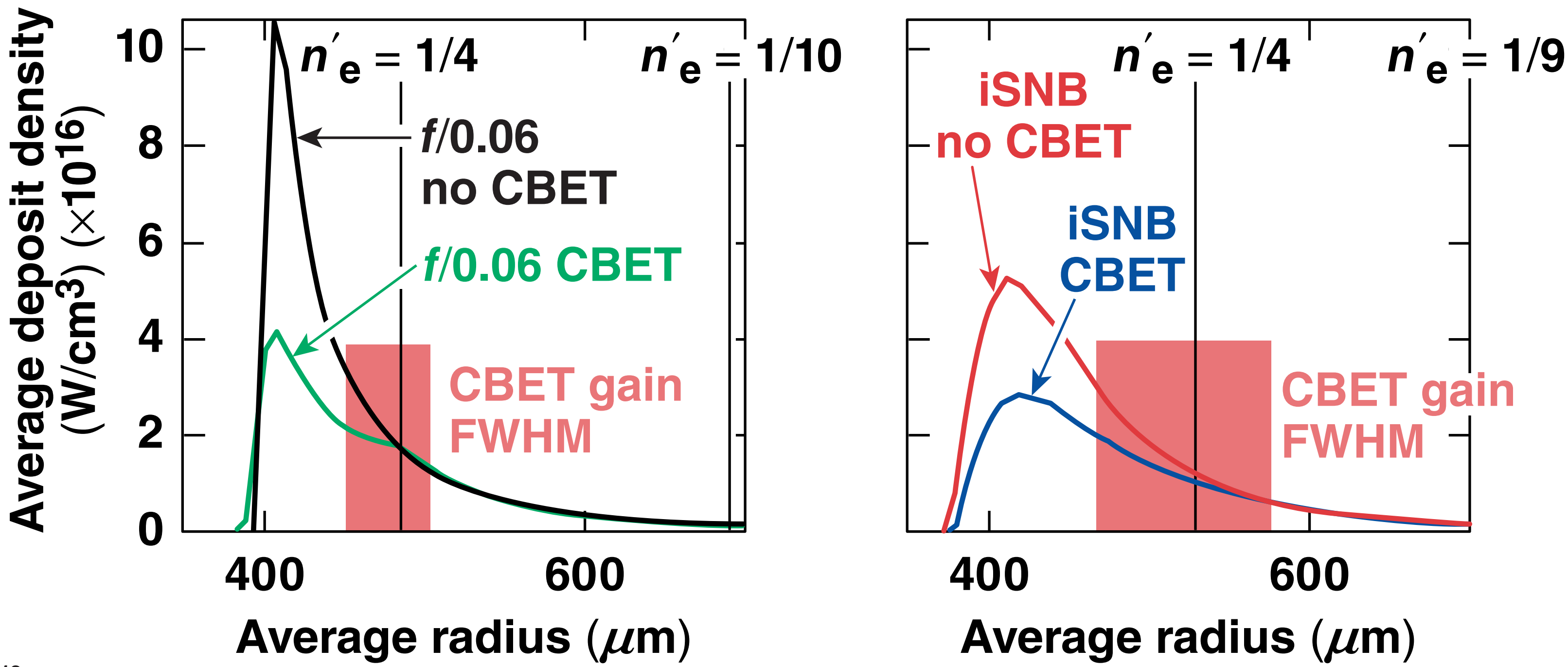
- The shot achieves high intensities (~8×10^{14} W/cm^2) to evaluate the effects of CBET





Simulations of OMEGA shot 6000 illustrate the combined effect of CBET and the nonlocal model on target dynamics

- The CBET effect reduces absorption at the radii interior to the interaction region, where the rays would have deposited their energy without significantly affecting the larger radii
- The iSNB model drives the target harder and widens the deposition and CBET regions as a result



TC11312

A ray suffers a frequency shift due to the time dependence of the electron density

- This frequency shift or chirp is a generalization of the common Doppler shift*
- The chirp is independent of a ray's direction; e.g., an inbound ray suffers the same chirp as an outbound ray
  - the chirp's sign does not depend on the plasma's expansion velocity relative to the ray's direction
  - it is not analogous to the common Doppler shift

$$\frac{dn_{refr}}{dt} = -\frac{1}{2}\frac{1}{n_{refr}}\frac{dn'_e}{dt}, \text{ where } \begin{cases} >0; \text{ red shift} \\ <0; \text{ blue shift} \end{cases}$$

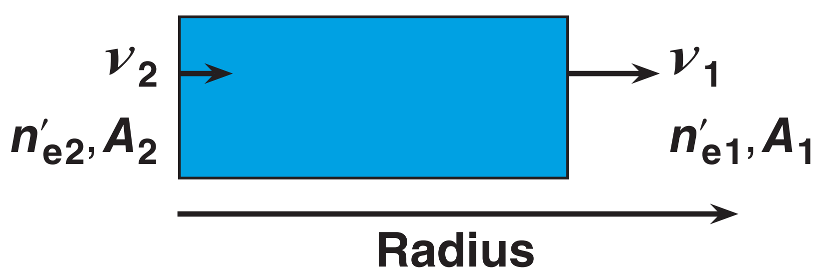
*T. P. Gill, *The Doppler Effect: An Introduction to the Theory of the Effect* (Logos Press Limited, London, 1965); T. Dewandre, J. R. Albritton, and E. A. Williams, Phys. Fluids 24, 528 (1981).

TC11313

The temporal derivative of the electron density is solved by invoking the equation of continuity

- In a simulation, the cell-centered value is calculated by solving the volume average of the temporal derivative using the divergence theorem

$$\left\langle \frac{dn'_e}{dt} \right\rangle = -\frac{1}{\text{vol}} \iiint \nabla \cdot \left[n'_e \nu_{\text{fluid}} \right] dv = -\frac{1}{\text{vol}} \oiint \hat{n} \cdot \left[n'_e \nu_{\text{fluid}} \right] dA$$



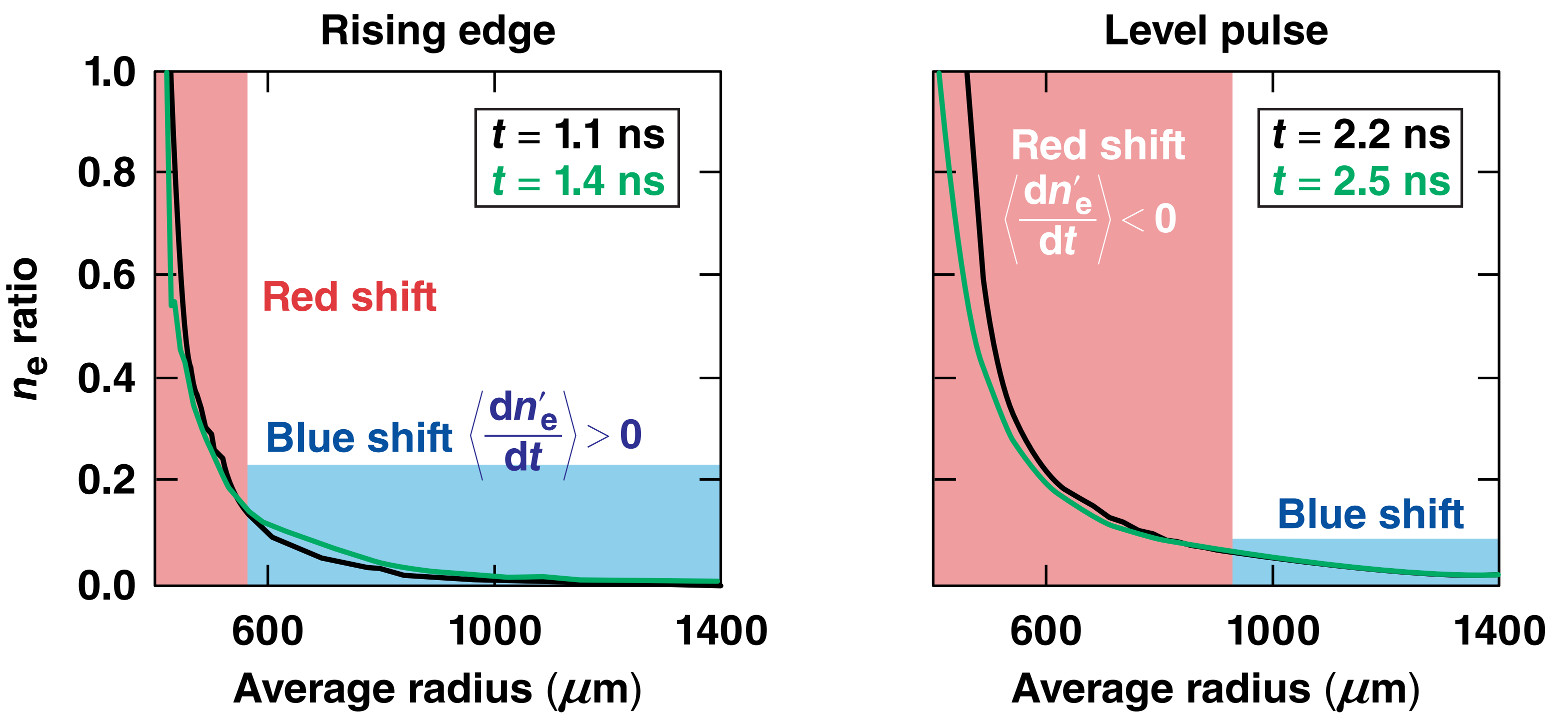
For a radial flow

$$\left\langle \frac{dn'_e}{dt} \right\rangle = n'_{e2} \nu_2 A_2 - n'_{e1} \nu_1 A_1$$

TC11314

The balance of the gradients determines the sign of the frequency chirp

- Near the critical surface, the negative electron density gradient overwhelms the positive radial velocity gradient results in $\langle dn'_e / dt \rangle < 0$, $dn_{refr} / dt > 0$, which generates a red shift
- Further out in the corona, $n'_e \lesssim 0.1$, the negative electron density gradient is lower and the increased positive radial velocity gradient and area cause $\langle dn'_e / dt \rangle > 0$, $dn_{refr} / dt < 0$, which generates a blue shift



TC11317

The rising edge of a pulse initiates a predicable sequence of Doppler-shift events

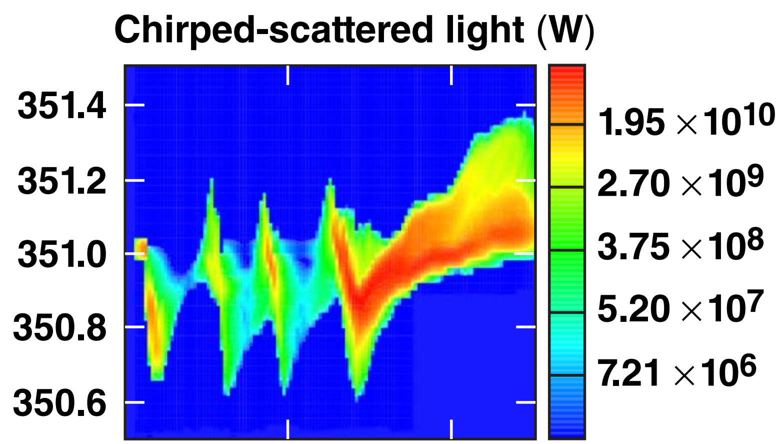
1) A red shift $\langle dn'_e/dt \rangle < 0$ occurs within a small volume near the critical density

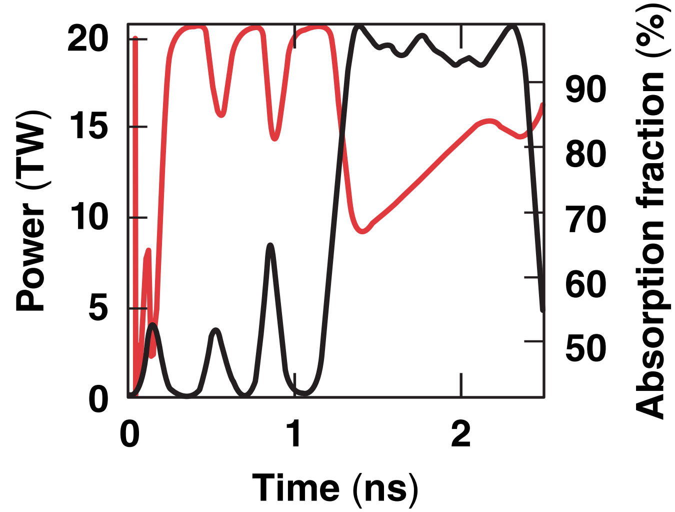
2) Next, a blue shift $\langle dn'_e/dt \rangle > 0$ develops within this volume and generates a diminishing outward propagating wave

   – the blue shift is not related to the falling edge, but caused by the rising edge

3) (optional) A sustained pulse (e.g., main) intensifies the red-shift region, $\langle dn'_e/dt \rangle < 0$ as the negative density gradient steepens and moves inward

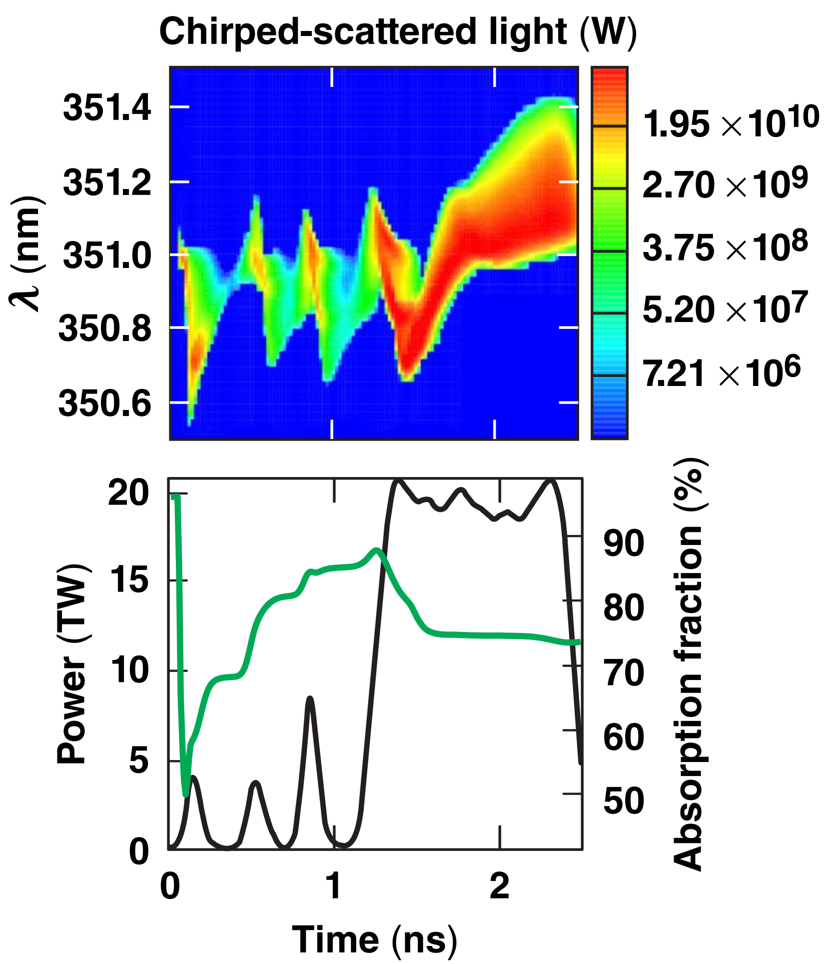
   – the volume expands and overwhelms the diminishing outward-propagating blue-shift region

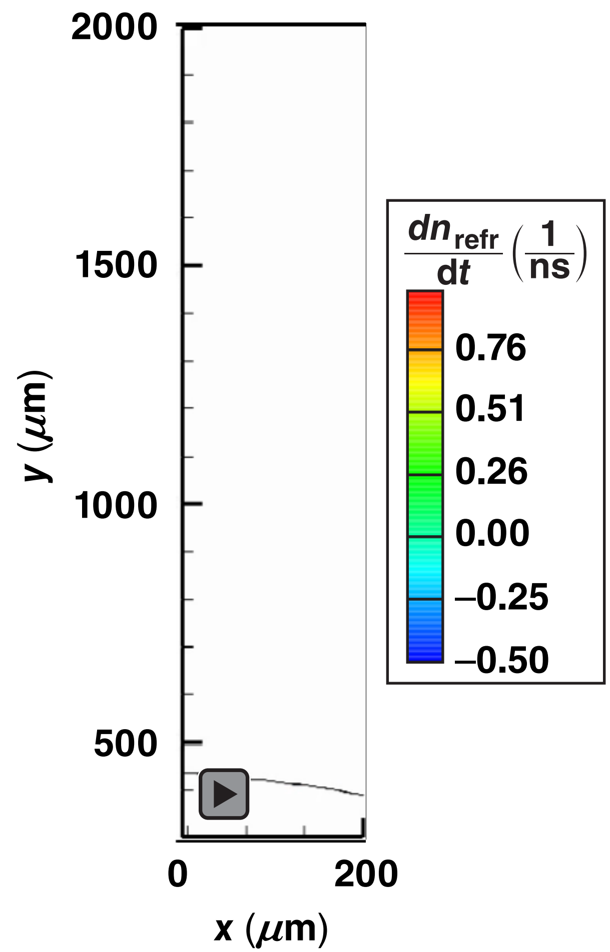




TC11318

As time progresses, the red-shift region expands, which eventually overwhelms the outer blue-shift region





TC11318a

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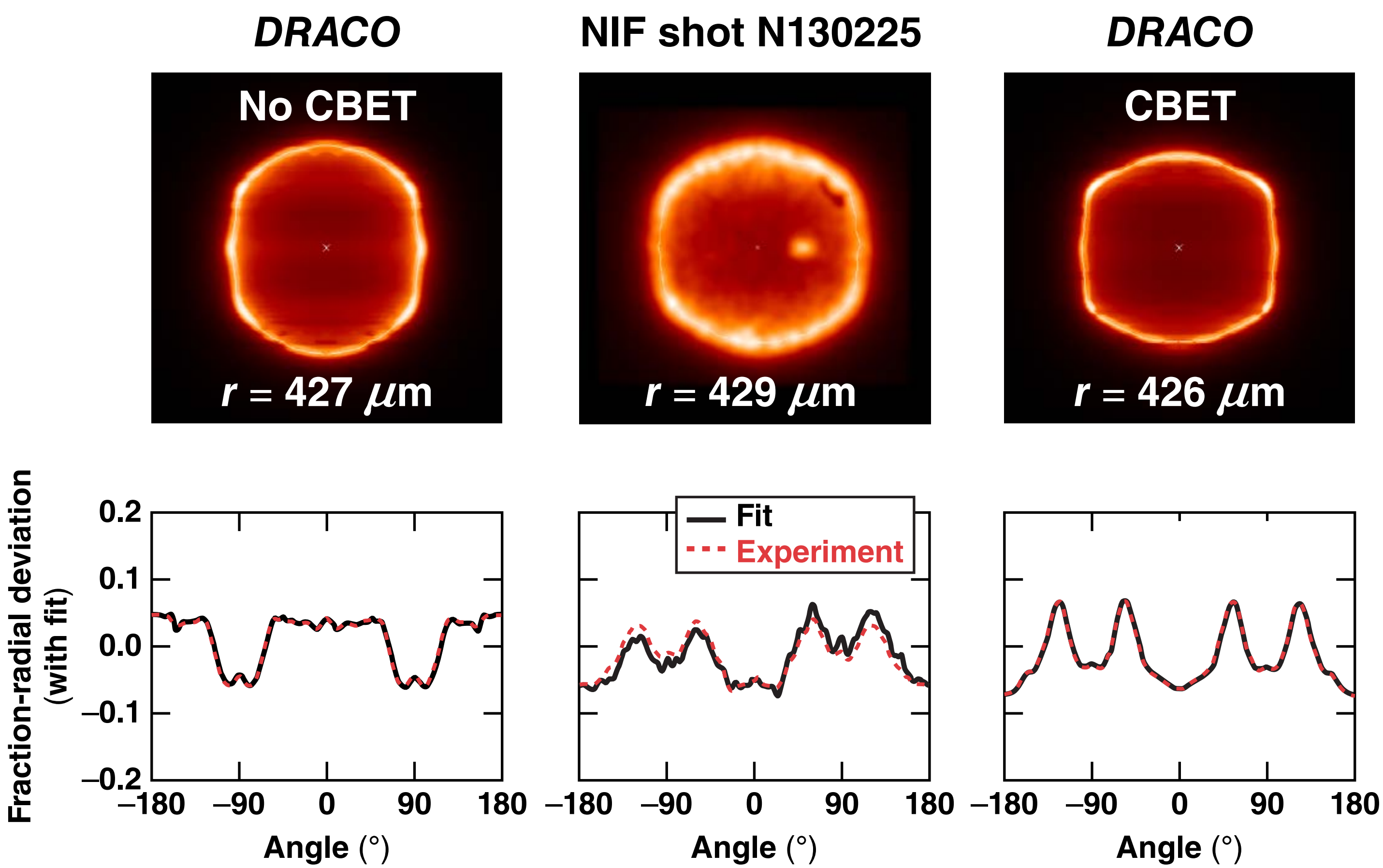
The higher-intensity NIF glass exploding-pusher target shot demonstrates the need of the CBET model

- N130225 is a 130-kJ, 1523-μm-diam target - Peak $I = 1.6 \times 10^{15}$ W/cm^2

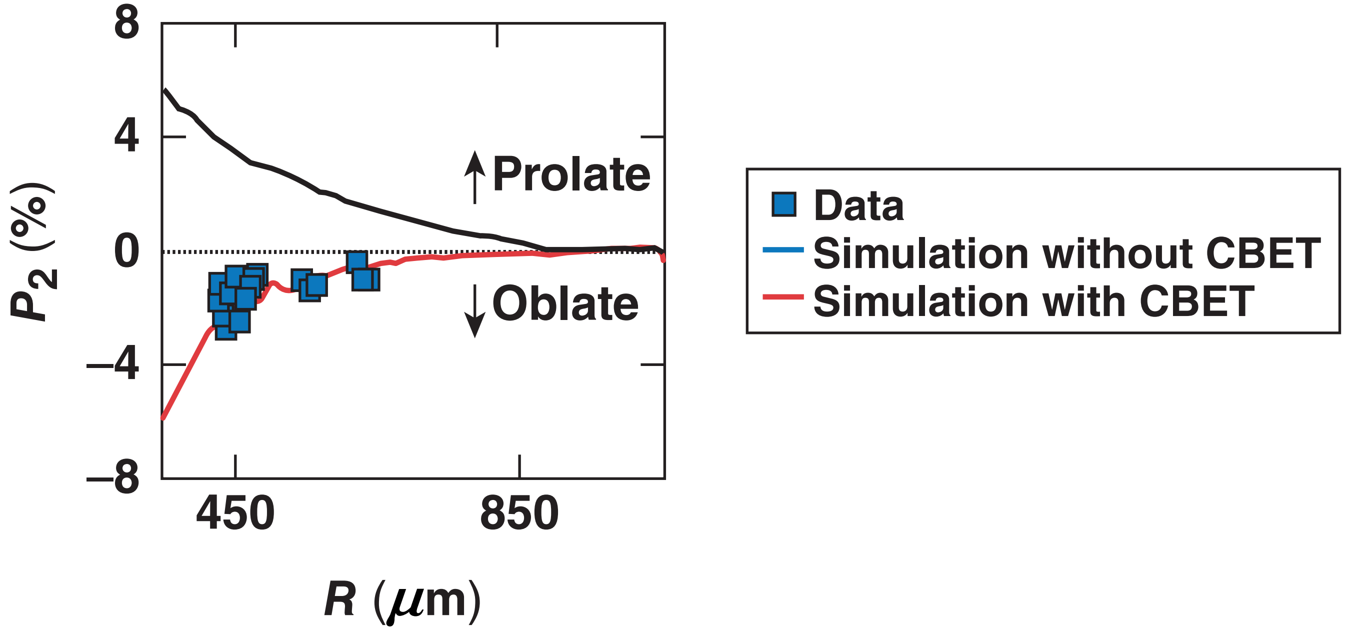


- **The simulation without CBET over drives the target equator**

TC10626d

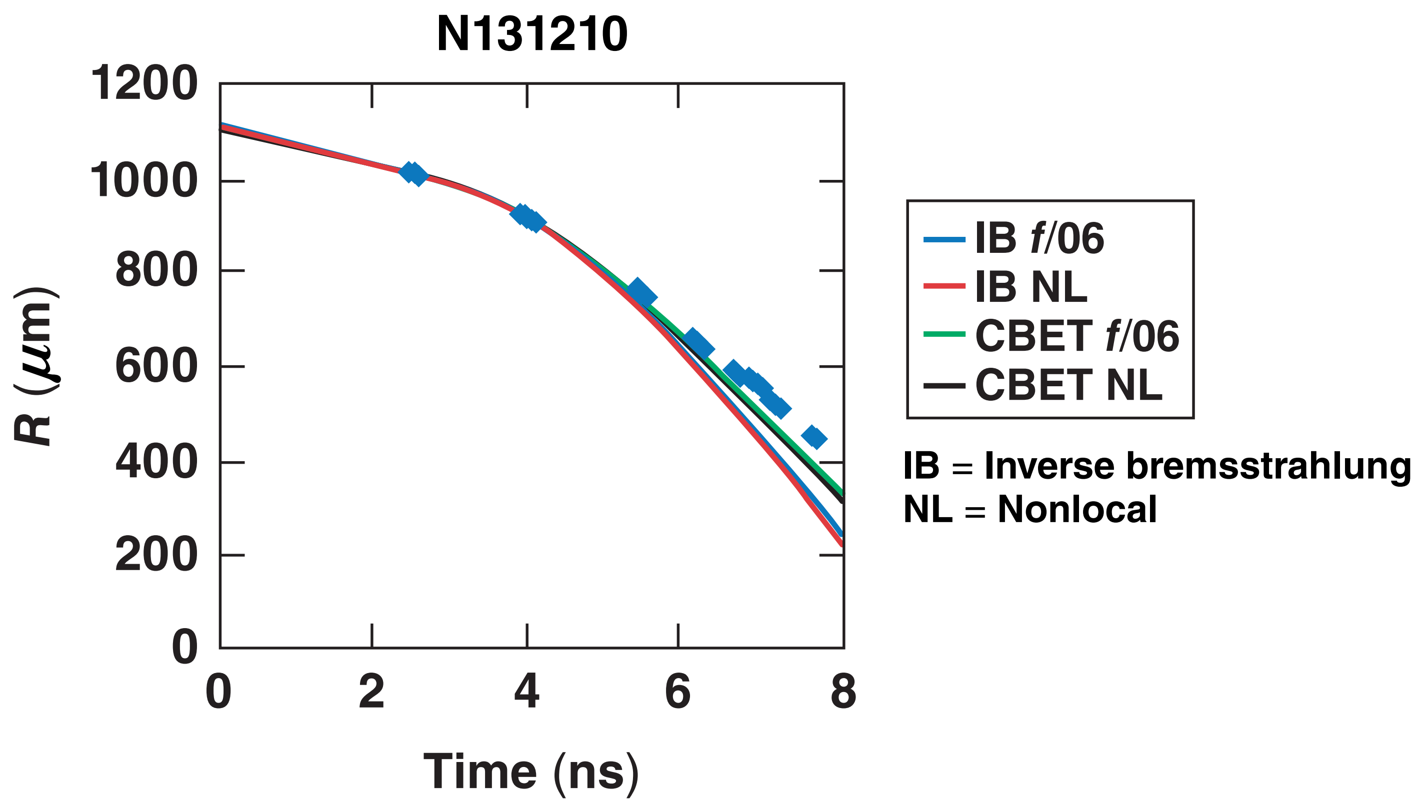
Simulations predict that the shell changes from prolate to oblate when CBET is included

- NIF shot N130128 observed this trend



TC11320

Simulations with CBET improve the agreement with the measured trajectories x-ray framing camera (XRFC)



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Absorption reduction caused by CBET can be mitigated in two different domains that can be combined

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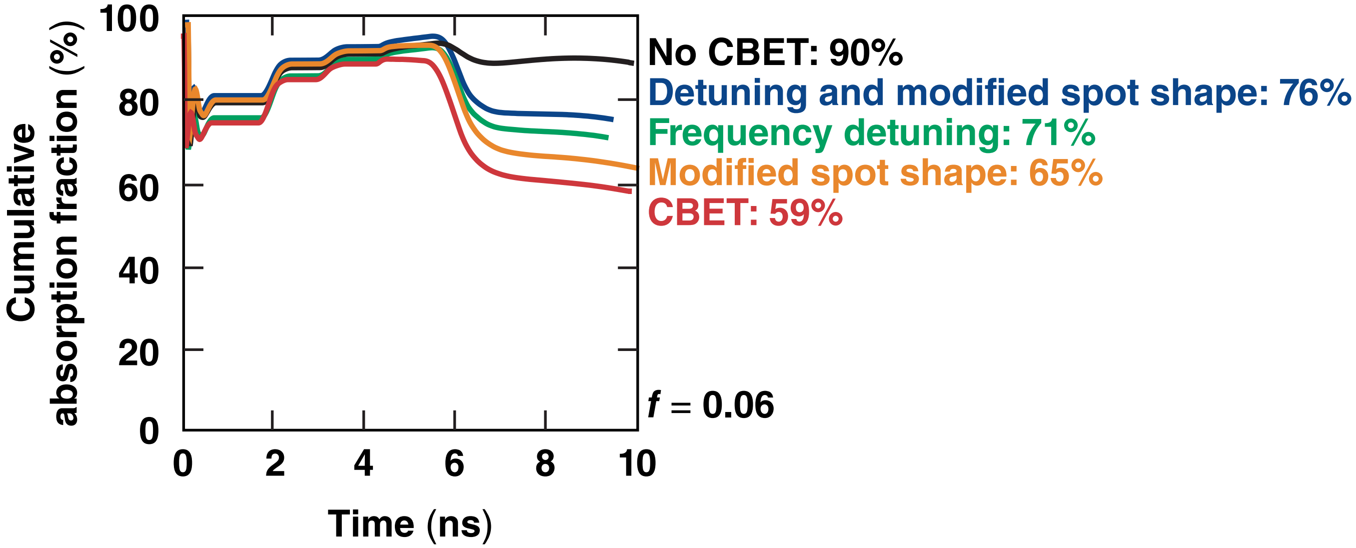
- Spatial domain (reduction of the interaction volume)
  - dynamic spot-shape changes; "zooming"*
    - can lead to severe imprint when using multizoned phase plates
  - static spot-shape design tailored to the target, e.g., spot masking
    - will not increase imprint
- Spectral domain (wavelength detuning)
  - detuning causes resonances to shift to lower interaction volumes
  - does not result in spot-shape distortion or imprint
  - all required technologies exist, i.e., no research and development
  - detuning may be more effective in PD

*D. H. Froula *et al*., this conference.

Detuning the northern and southern laser frequencies helps recover drive diminished by CBET

- SBS has a resonance condition for the transfer of energy between rays by means of an intermediary ion-acoustic wave
- The resonance condition depends on the wavelength difference $\Delta\omega$ between the beams; increasing $\Delta\omega$ reduces or eliminates the portion of the beam that satisfies this condition
- Detuning the wavelengths for the equatorial beams in the northern and southern hemispheres by ±6-Å (UV) increases laser coupling by 12%



Mitigating CBET by frequency detuning and spot-shape modification recovers over half of the drive energy lost to CBET.

TC11015

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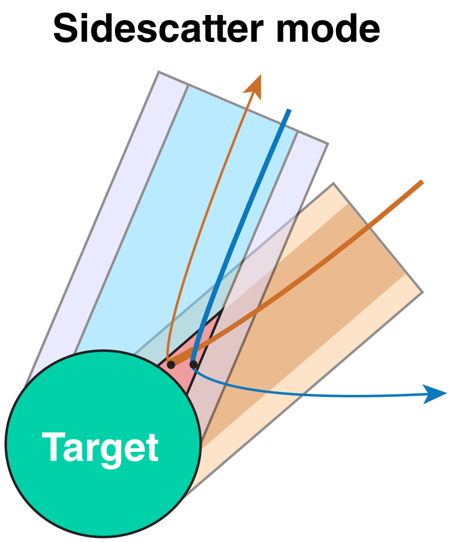
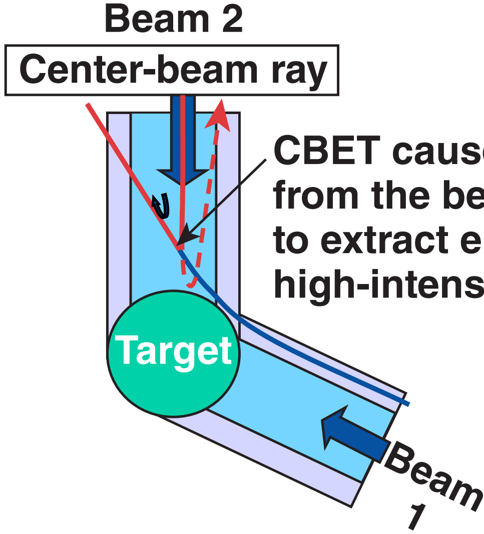
Wavelength detuning uniquely affects the two CBET modes in direct drive

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





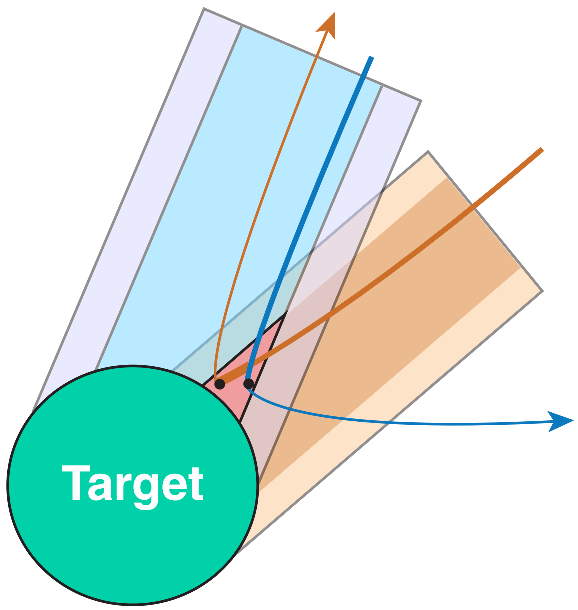
- The $\Delta\omega$ sign effects gain/loss
- Smaller interaction volumes and "throw" minimizes impact

- The $\Delta\omega$ sign does not effect gain/loss unless large magnitude
- The $\Delta\omega$ sign shifts the resonance into lower interaction volumes

TC11305a

Wavelength detuning has minimal impact in sidescatter mode in direct-drive targets

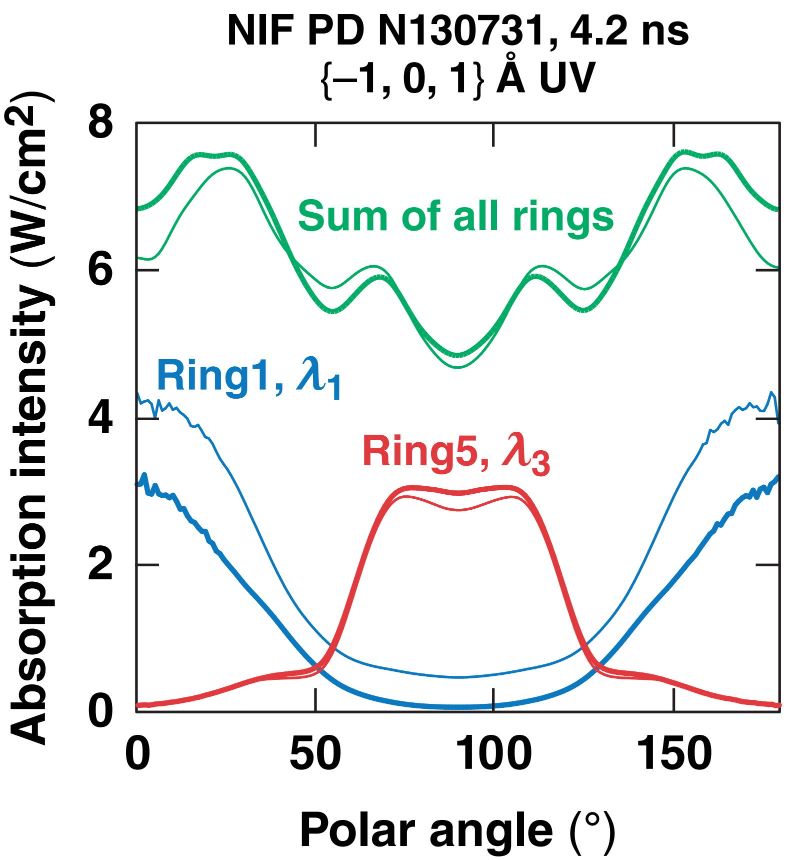
Sidescatter mode



- For two inbound/outbound beams, wavelength detuning can transfer energy from one beam to another (analogous to indirect drive)
  - the interaction volume is small, especially over the equator
  - the change in propagation distance is small; i.e., small throw and will not have a strong effect on drive
  - this is not useful for direct-drive implosions (symmetric or PD)

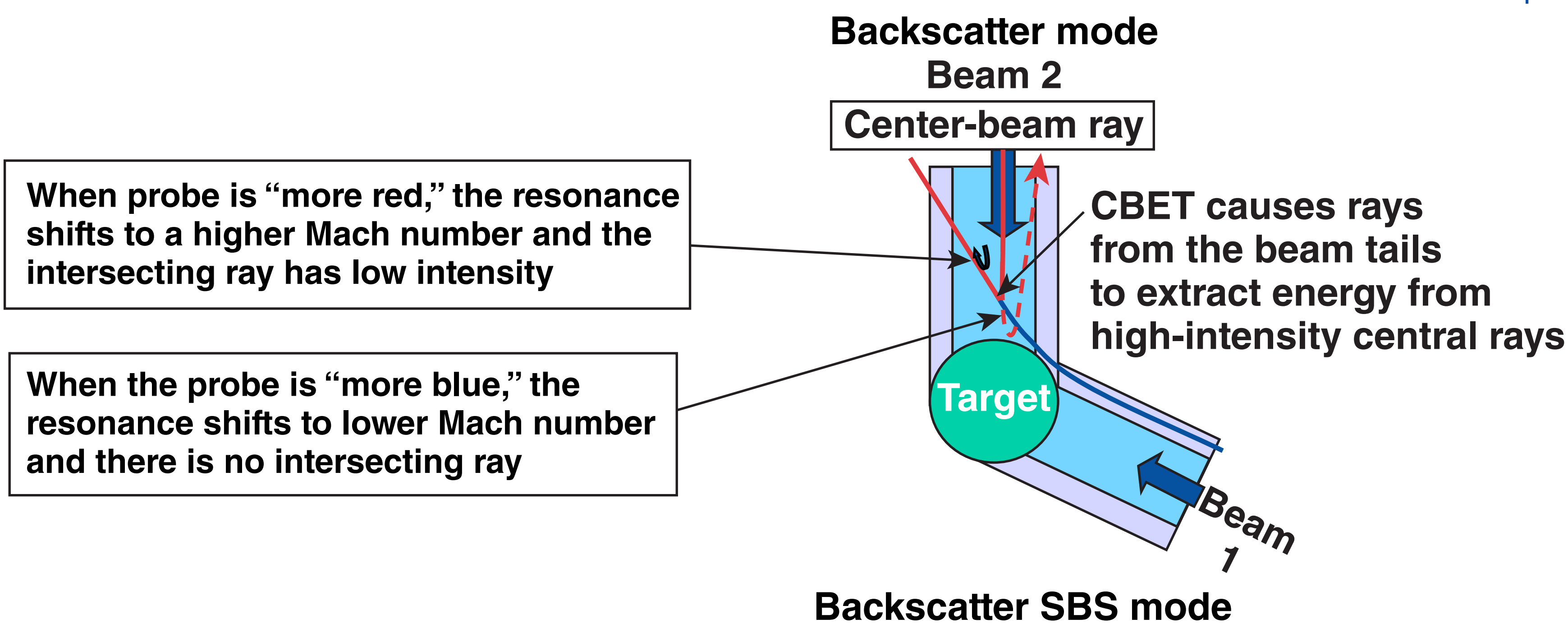
TC11305b

Using cone-to-cone transfer is not beneficial for direct drive sidescatter mode



- There is an apparent benefit in the absorption fraction per cone, however, this is a small net effect on drive
  - the exchange is "local" because of the lack of "throw" from propagation compared to what exists in indirect drive
  - will not significantly benefit the equator because of the small overlap
- Will not significantly alter symmetry
- Will not significantly improve overall absorption and drive

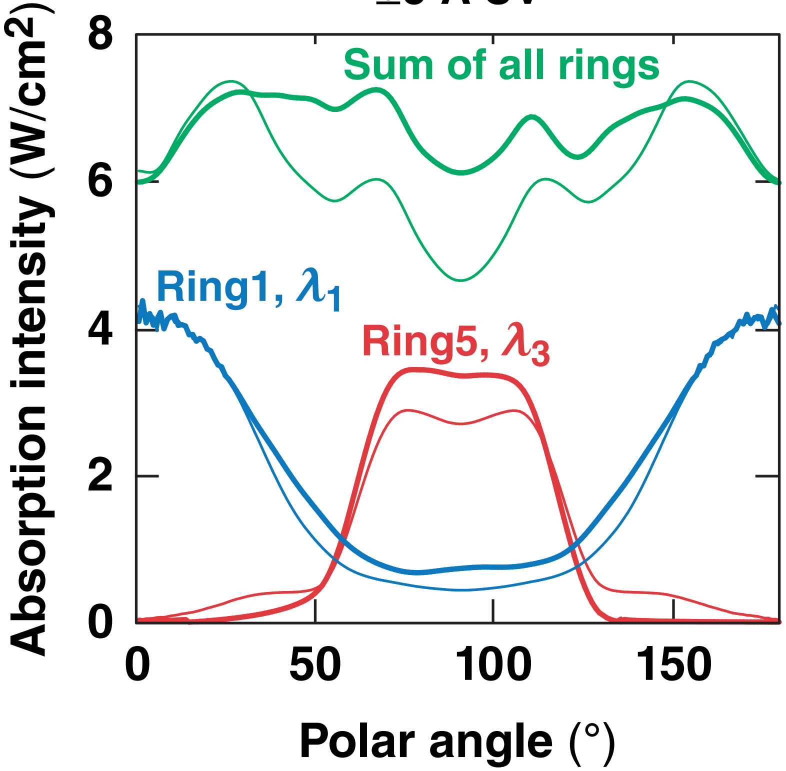
Successful wavelength detuning shifts the resonance location sufficiently to mitigate CBET



- The amount of $d\lambda_0$ must compensate for the tails of the probe beam
  - works for both symmetric and PD
  - north–south asymmetries exist for small $d\lambda_0$ and large compression but can compensate
  - requires larger $d\lambda_0$ detuning to be useful (i.e., > ±2-Å UV)
  - tailoring the spot shape will help limit the required $d\lambda_0$

TC11327

Using hemispherical $d\lambda_0$ will increase the total absorption and benefit the drive symmetry



- The absorption for all rings benefit in the equatorial region when using hemispherical detuning
  - sidescatter mode is inactive because each hemisphere has the same λ_0
  - rays that pass over the equatorial region have increased absorption, even in Ring1

TC11326a

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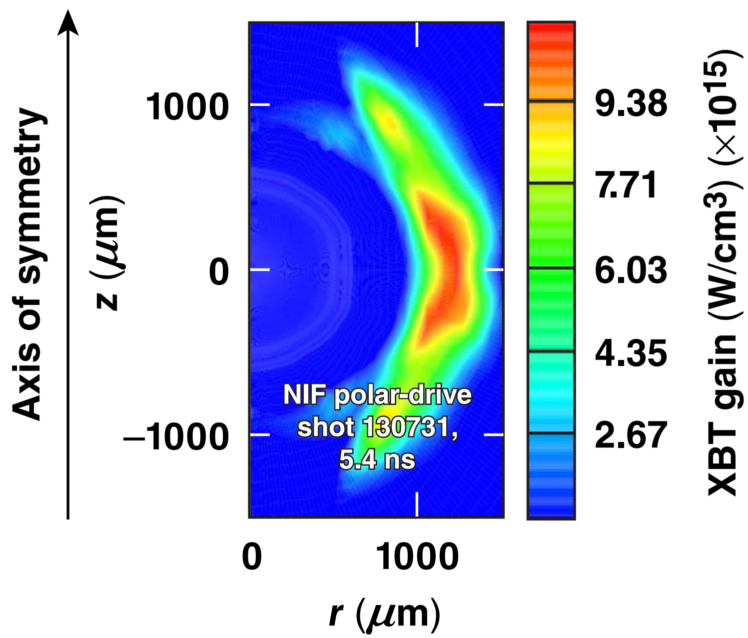
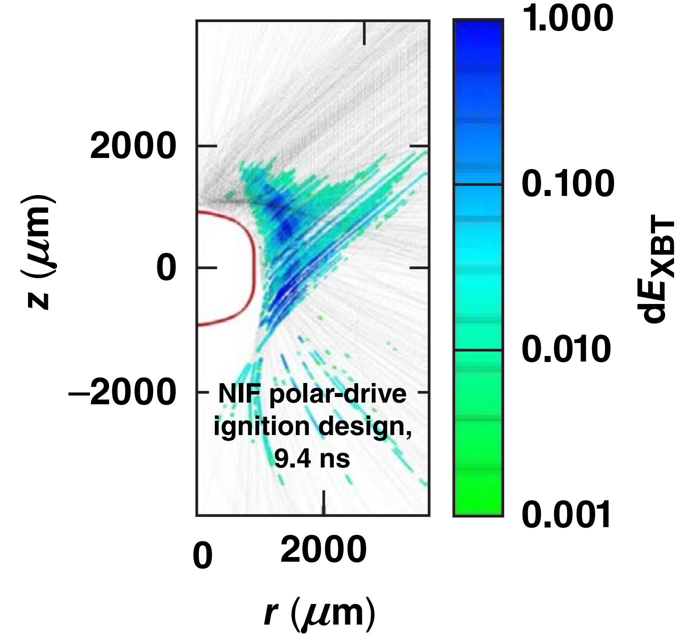
The majority of CBET occurs over the equatorial region in polar drive

CBET gain, all beams



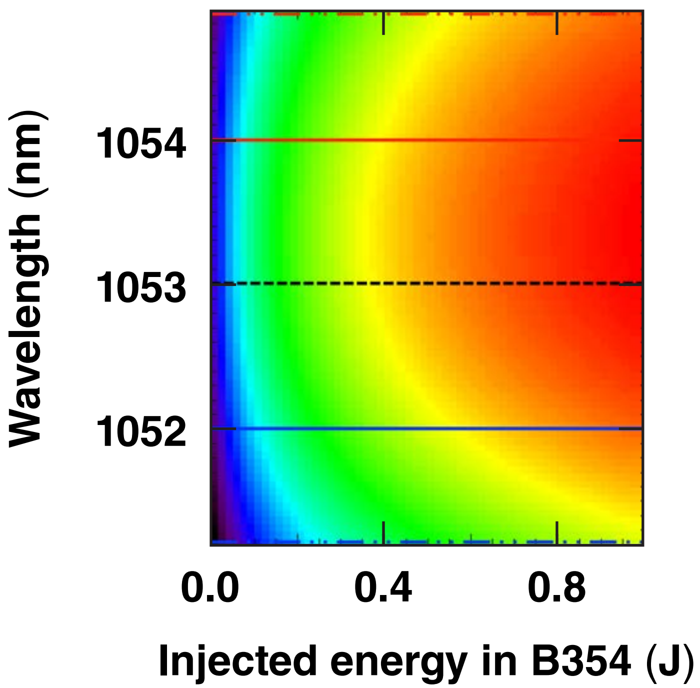
CBET energy loss from
an equatorial beam because pf
the north and south equitorial rings

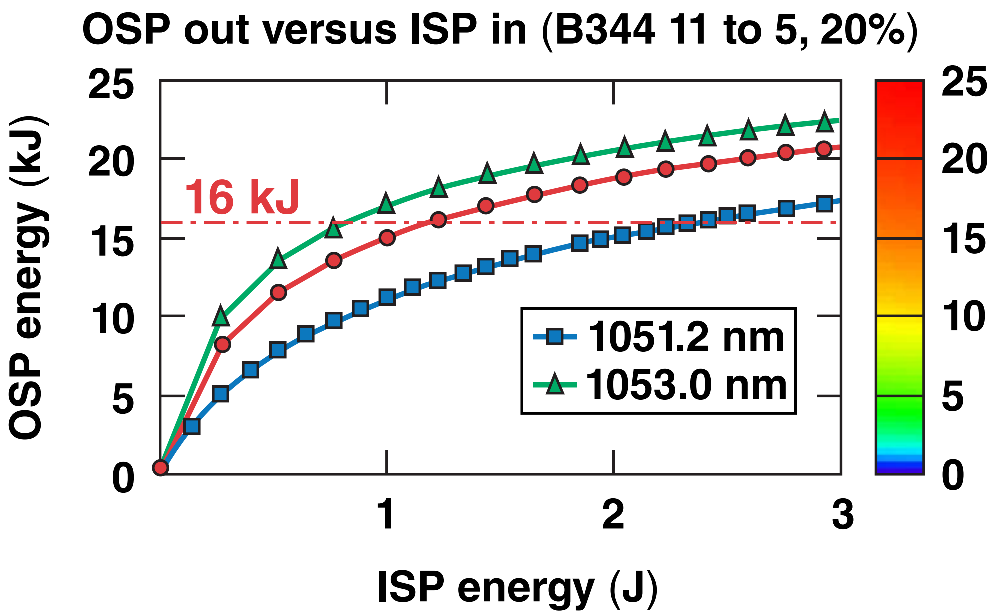


- CBET reduces the laser drive by as much as 30%, making CBET mitigation the most important design issue
- CBET occurs in a changing portion of the corona where the resonance condition is met
- Opposing $d\lambda_0$ in each hemisphere offers the best CBET mitigation
  - – requires "rewiring" the NIF fiber front end
- Detuning the hemispheres changes the location of this interaction region; the interaction region vanishes only in the large detuning limit

On the NIF, the desired dλ_0 of ±6-Å UV seems achievable with modifications to the reflection absorption baffles

- The regen and main amplifiers on the NIF are predicted to support the desired ±6-Å UV detuning*





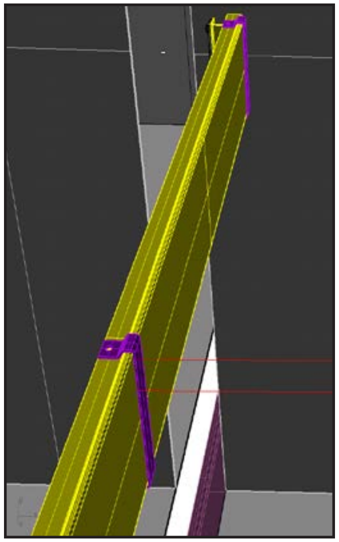
- Shiny metal clips supporting the Armor glass (baffles) currently prevent increasing the detuning range caused by the potential retroreflections
- LLE and LLNL are working together to address meeting the goal of ±6-Å UV detuning

*S. Yang *et al*., teleconference presented at Lawrence Livermore National Laboratory, Livermore, CA (11 March 2014).

TC11337

The $d\lambda_0$ on the NIF in the current configuration will be able to produce the initial smaller detuning range in most beams

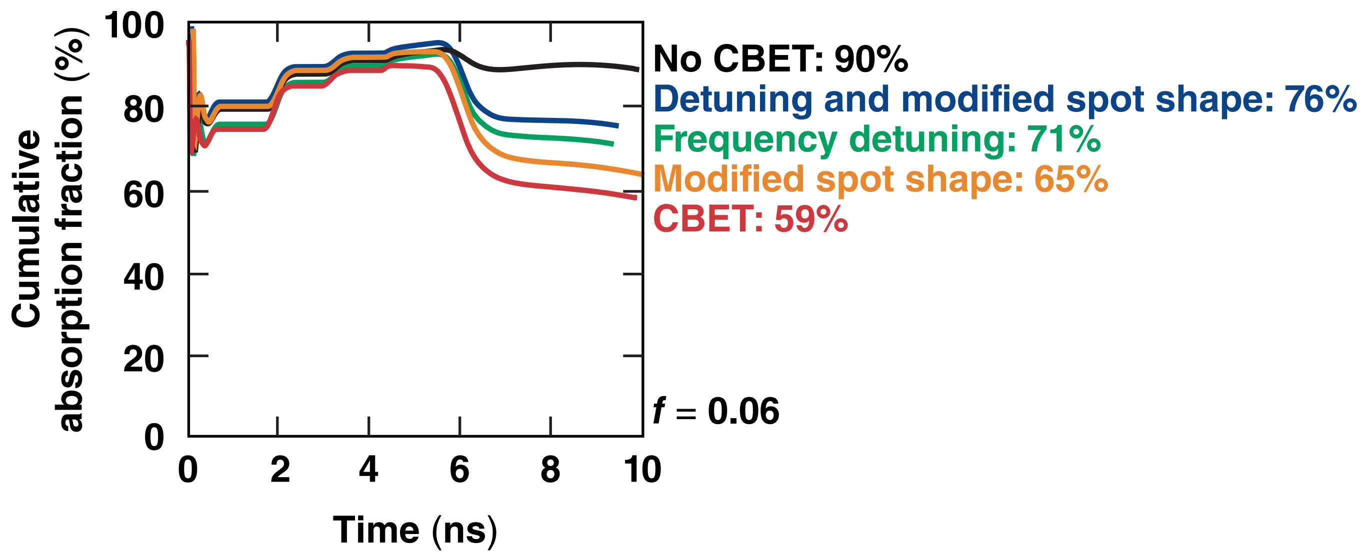
- The full tuning range is possible in the regen and main amplifier chain
- Some beams are currently restricted in the maximum ± detuning due to shiny metal clips supporting the Armor glass (baffles) because of potential reflections*



*B. MacGowan and L. Siegel, teleconference presented at Lawrence Livermore National Laboratory, Livermore, CA (8 April 2014).

Detuning is the most promising of the techniques planned for CBET mitigation

- Mitigation techniques also include
  - modification to the spot shape to reduce energy near the beam edges
  - increasing equatorial beam energy: 10% increase in the overall power produces a 5% increase in the absorbed power (must remain within power and fluence limits)
- Mitigating CBET by frequency detuning and spot-shape modification recovers over half of the drive energy lost to CBET

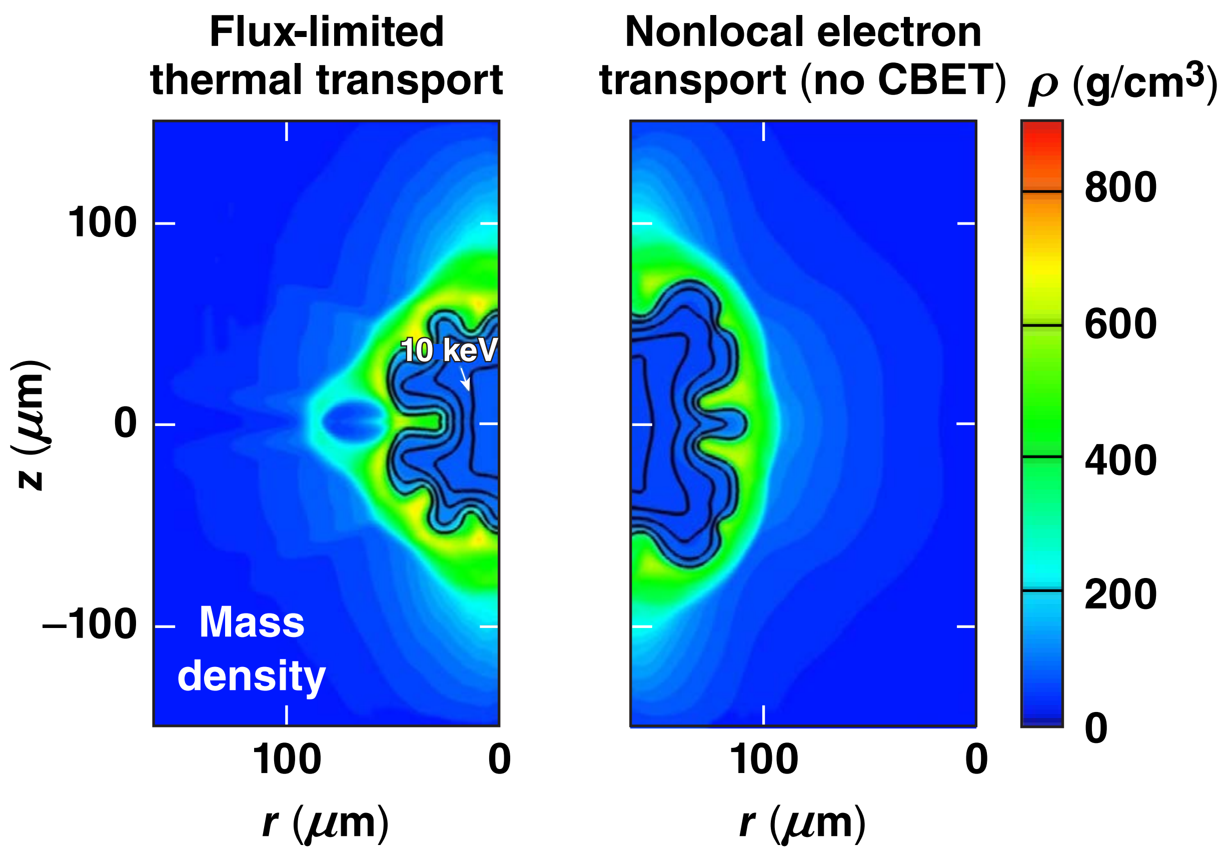


TC11015a

The polar-drive–ignition point design is being retuned to include CBET

- The point design has been retuned to include the effects of nonlocal heat transport, modeled with the implicit Schurtz–Nicolaï–Busquet model
- Increased drive from nonlocal heat transport partially compensates for the decrease in equatorial drive caused by CBET

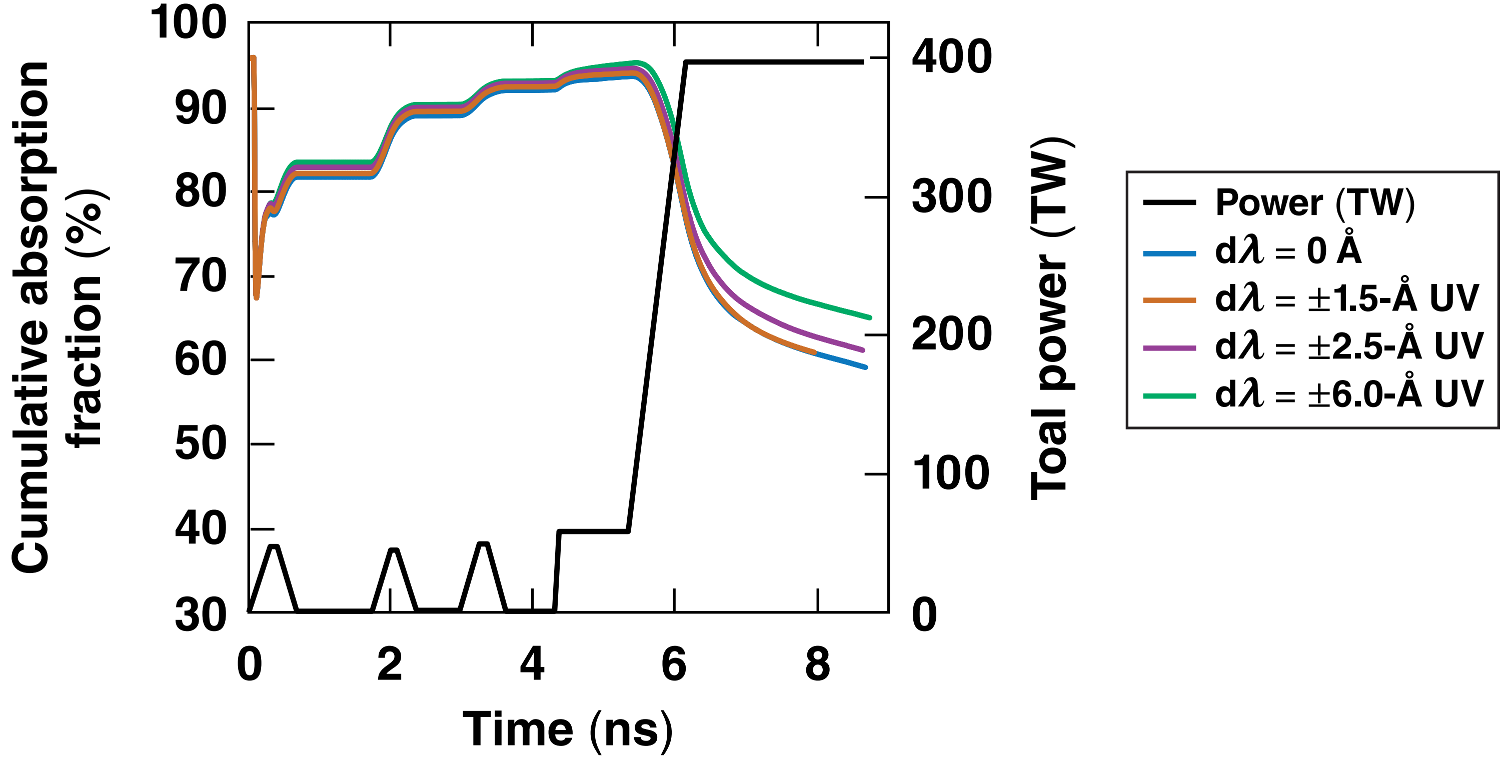
Baseline design without CBET or nonlocal heat transport	
V_{imp} (μm/ns)	367
CH thickness	39 nm
$IFAR_{LLE}$	24
In-flight α	2.2
Convergence ratio	30
Peak ρR (g/cm^2)	1.4
Fuel mass	1.34 mg



TC11333

Hemispherical detuning simulations with nonlocal electron transport show the same trend as with $f = 0.06$

- While ±2.5-Å (UV) has too small an effect, ±6-Å UV restores a significant amount of the drive lost to CBET
- A conclusion will be drawn when the simulations reach the end of the pulse (10 ns, including a ±12-Å UV case for reference)



TC11368

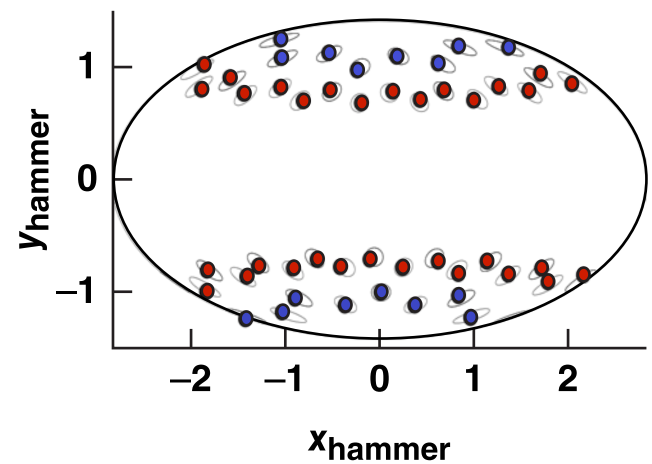
CBET mitigation strategy for NIF polar drive

- CBET overview
- Modeling CBET
- Effects of CBET
- Comparison to NIF experimental results
- CBET mitigation schemes
- Effects of $d\lambda_0$
- Employ hemispheric $d\lambda_0$
- **Employ $d\lambda_0$ on the current NIF configuration**

Using $d\lambda_0$ on the NIF in the current configuration is possible while maintaining symmetry

- Currently NIF is configured with three wavelengths
  - cones: {23.5°}, {30.6°}, {44.5° and 50°}
  - northern and southern hemispheres are identical
- Limits the $d\lambda_0$ shift options
  - nonideal cone-to-cone option (i.e., sidescatter mode)
  - swapping cones in one hemisphere (use backscatter mode)
    - compensation strategies are necessary to minimize any north–south asymmetries and *m*-mode structure
    - compensate using asymmetric pulse shapes, asymmetric pointings, reorganizing PD pointing, and quad splitting
      - produces near-symmetric drive

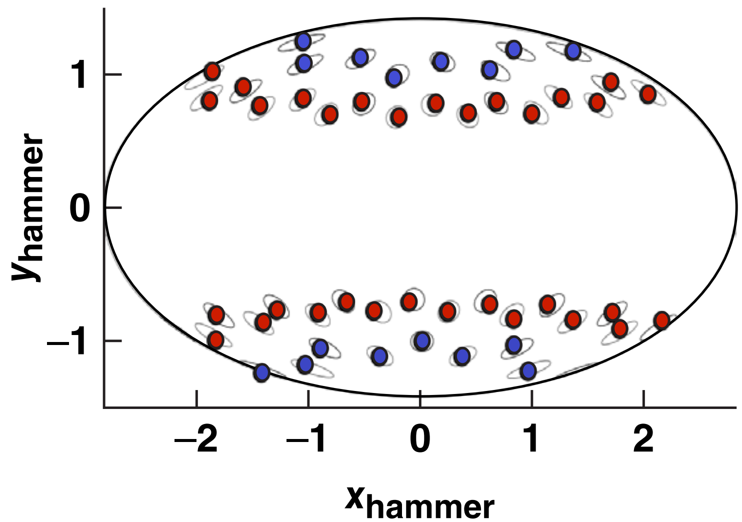
Color/port arrangement



The current $d\lambda_0$ option on the NIF does not allow for two different colors in each hemisphere

UR LLE

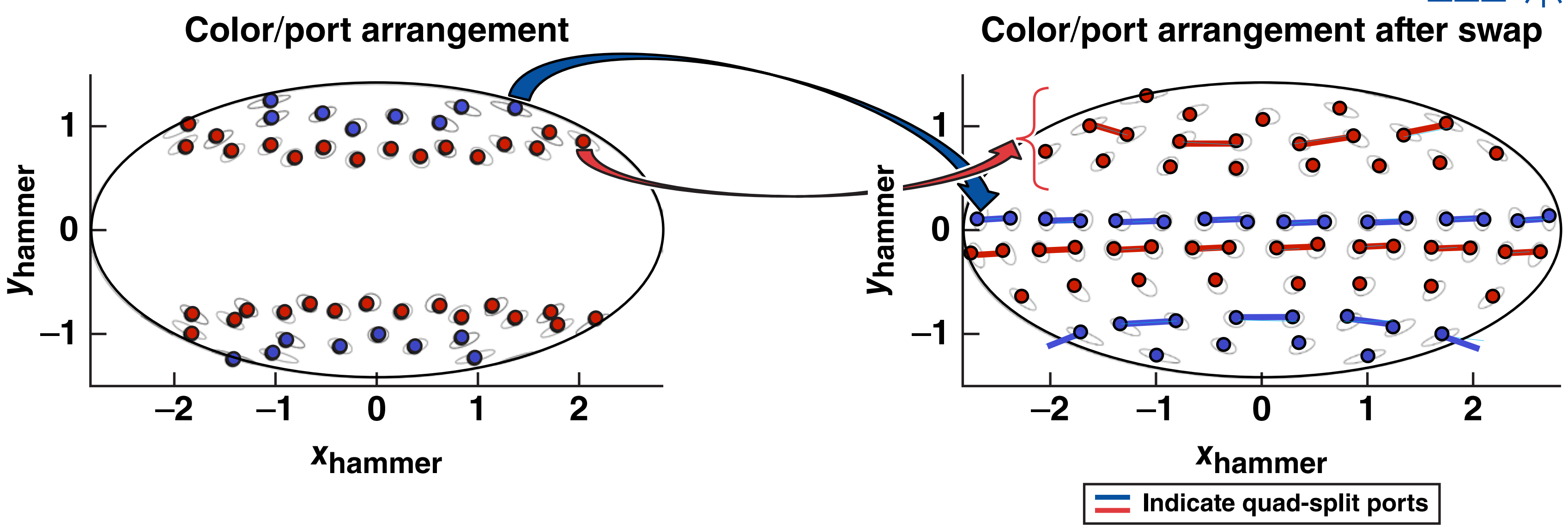
Color/port arrangement currently on the NIF



- Two colors are assigned; Cones 1 and 2 are blue; Cone 3 is red
  - northern and southern hemispheres are identical
- Typical PD repointing schemes would have the same color over the equatorial region in each hemisphere
- However, swapping cones via repointing in one hemisphere will place two colors over the equatorial region

TC11338

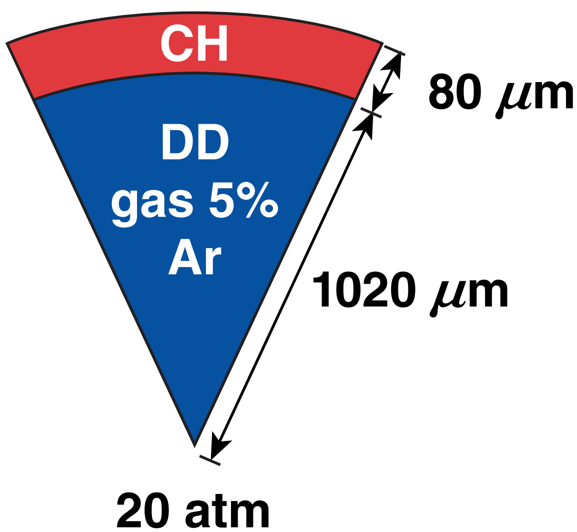
North–south symmetry (spot location, ϕ spacing and quad split) configuration achieves a near-spherical implosion

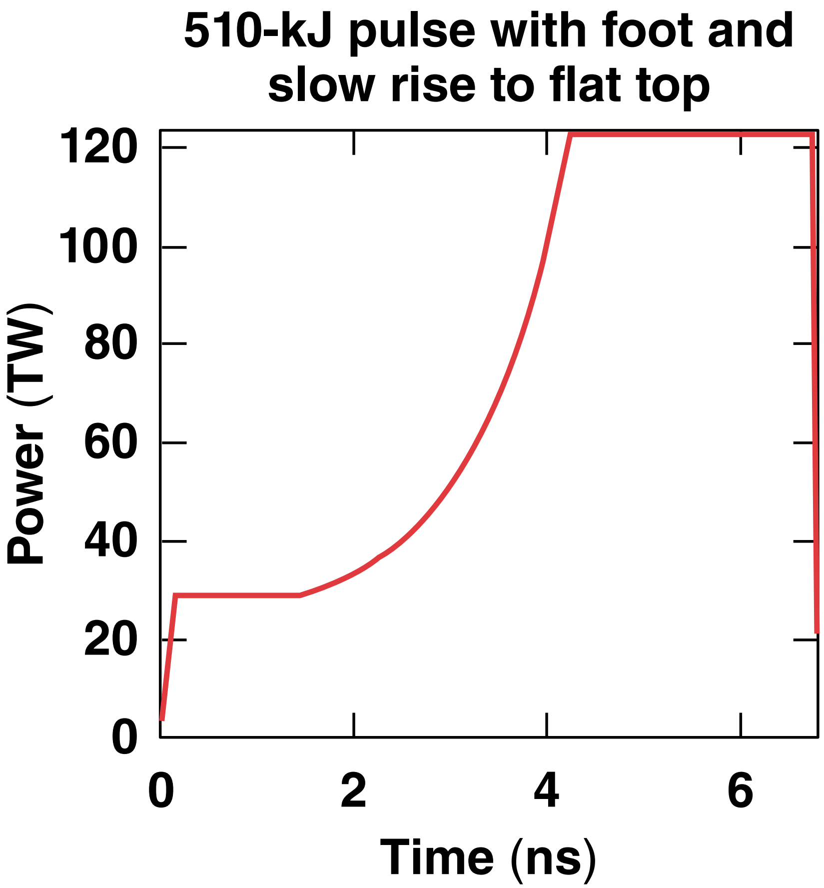


- Two colors are assigned: Cones 1 and 2 are blue; Cone 3 is red
- Wide ellipses are used at the pole or mid-latitude
- Narrow ellipses are used in any port repointed to the equator
- Each latitude (north–south) has the same port configuration; e.g., number and quad split
- North–south asymmetry in pulse shapes are required to compensate for differences in dθ shifts
- North–south asymmetry in polar repointing angles compensates for on-target shape changes caused by larger dθ

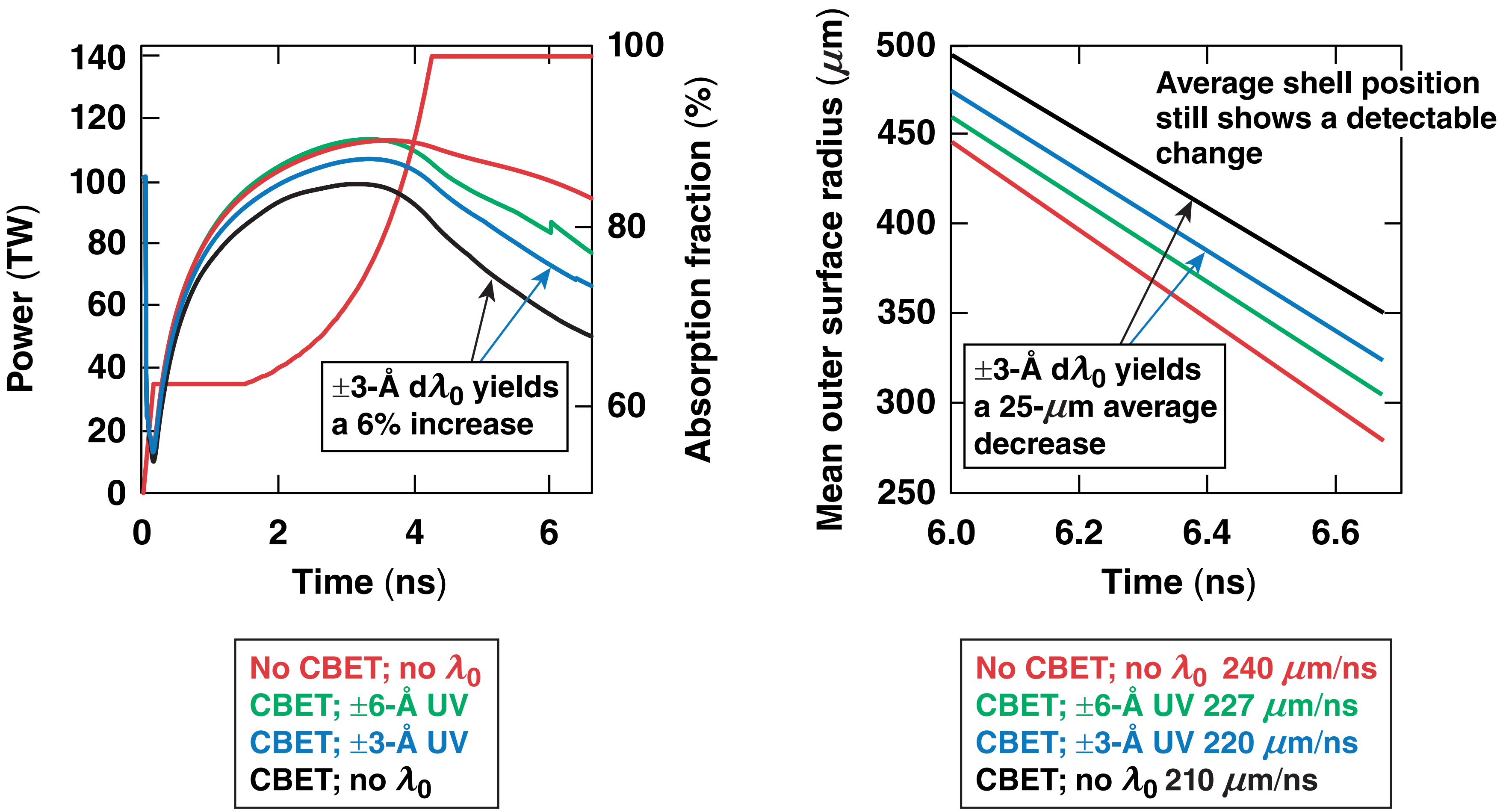
TC11338a

NIF shot N130731 was used as the simulation's basis for the dλ_0 CBET mitigation scheme using the current NIF configuration





The current NIF configuration can achieve north–south $d\lambda_0$, which increases the total absorption and shell velocity

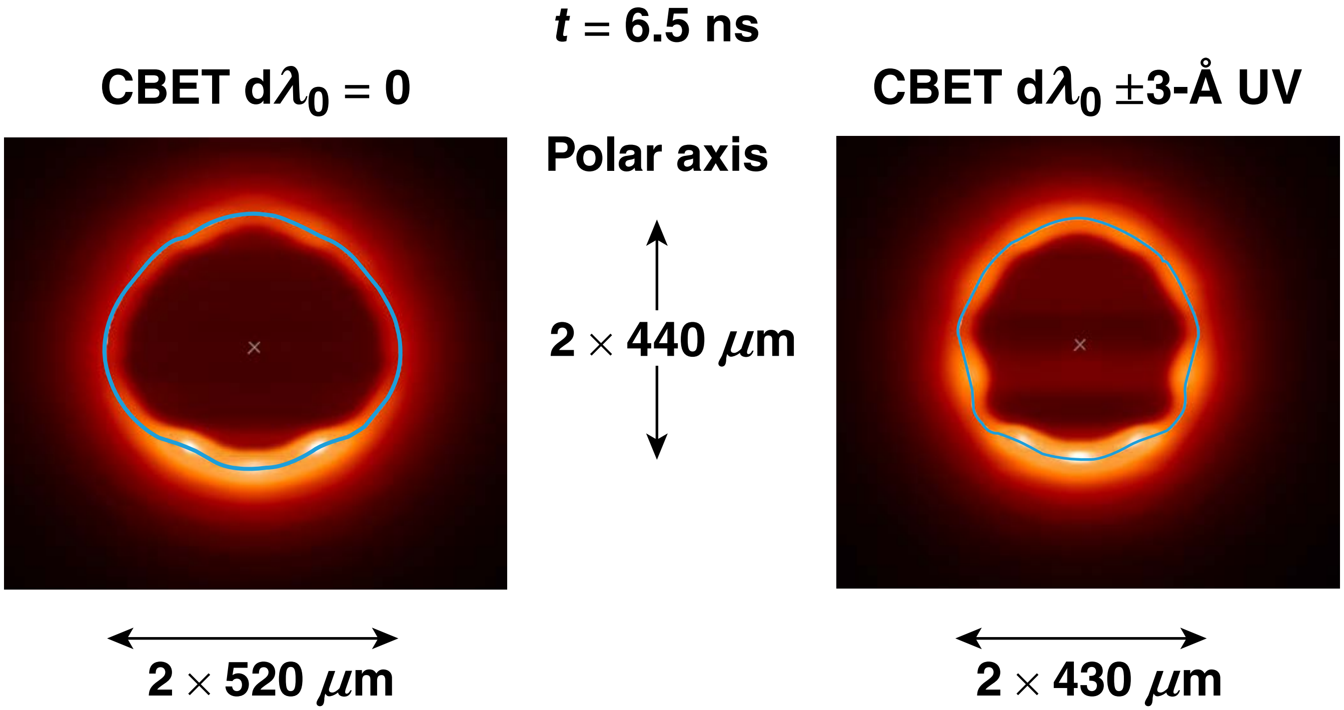


- The dR of the shell at the equator is ~90 μm

TC11342

Simulated self-emission images illustrate the predicted measurable effect of initial wavelength detuning tests

Wavelength detuning using NIF's current configuration.

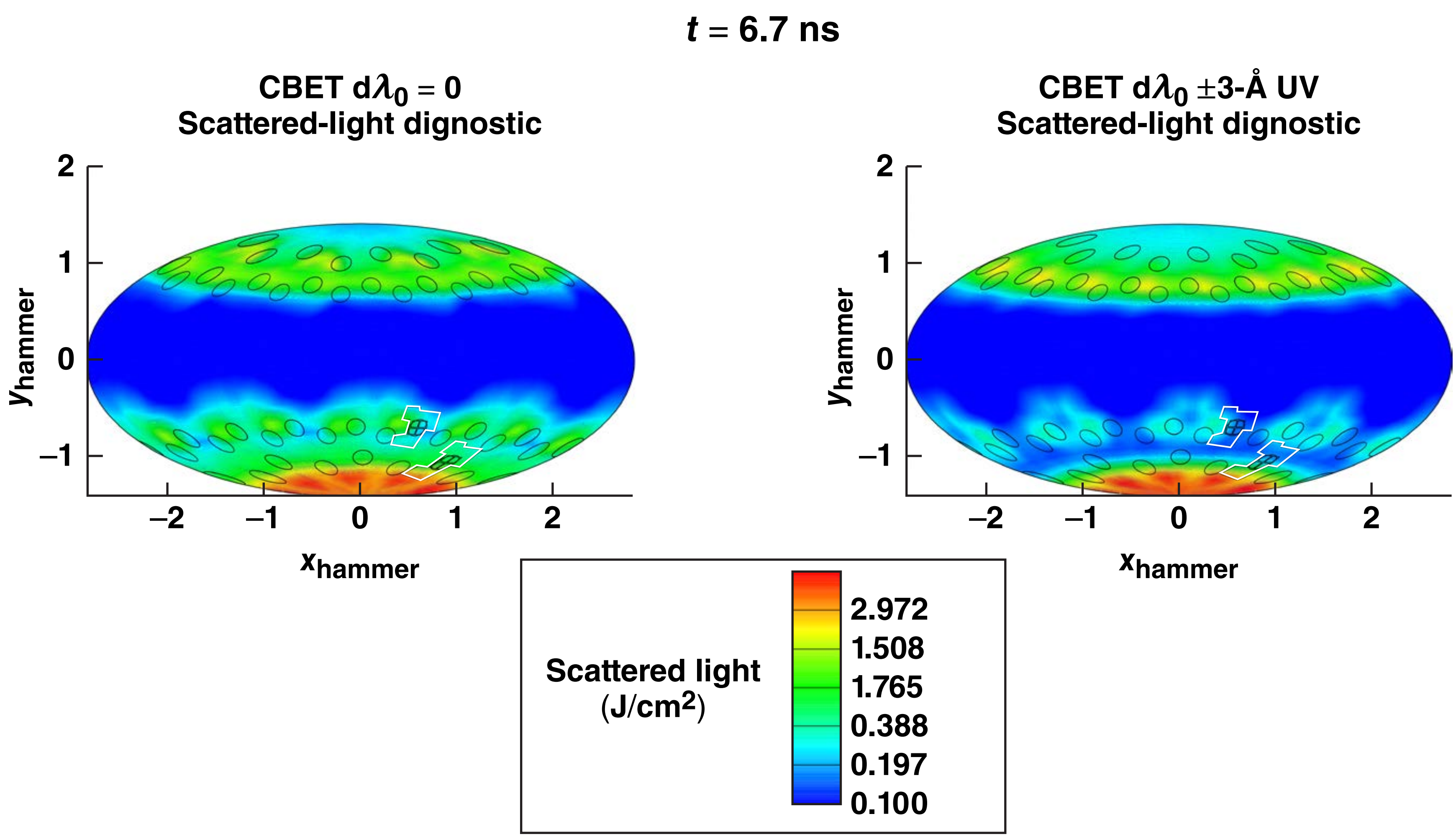


±3-Å dλ_0 yields ~90-μm dR at the equator

- The change in shape cause by dλ_0 CBET mitigation enhances equatorial drive as predicted; dR ~ 90μm

The near-backscatter imaging plates are positioned to detect the changes

Wavelength detuning using NIF's current configuration



Summary/Conclusions

Simulations indicate that wavelength detuning is a promising cross-beam energy transfer (CBET) mitigation scheme achievable at the National Ignition Facility (NIF)

UR LLE

- The CBET effect increases scattered light through the stimulated Brillouin scattering (SBS) of outgoing rays that removes energy from incoming high-energy rays
- The wavelength detuning and initial spot-shape mitigation schemes work together with pulse modification to offer a potential point design for polar drive (PD) at the NIF
- The current NIF configuration allows for initial testing of the wavelength mitigation scheme