Cross-Beam Energy Transfer Mitigation Strategy for NIF Polar Drive

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

J. A. Marozas
University of Rochester
Laboratory for Laser Energetics

44th Annual Anomalous Absorption Conference
Estes Park, CO
8–13 June 2014
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


University of Rochester
Laboratory for Laser Energetics
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
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 $k_a^*$

\[ k_a = k_{\text{pump}} - k_{\text{probe}} \]

- The resonance condition peaks when the matching condition is met

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

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

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

- The exponential CBET gain or loss factor is given by

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

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

Resonance function

Matching condition

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

$$\eta > 0; \text{gain} \quad \eta < 0; \text{loss}$$

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

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

---

** 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**

- CBET causes rays from the beam tails to extract energy from high-intensity central rays

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

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

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

Matching conditions:

\[ V_{\text{fluid}} \lim_{M c_a \hat{r} = \frac{\Delta \omega - M \cos \theta}{|k_a| c_a} \hat{r}} \]

- The resonance condition still peaks where the fluid is supersonic (small \( \Delta \omega \))

- However, the \( |k_a| \) is much smaller and the angle \( \theta_{k_a} \) can be near orthogonal, which implies that the \( k_a \cdot V_{\text{fluid}} \) 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

- 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 $\pm 6$-Å UV)
  - dominated by the $k_a \cdot V_{\text{fluid}}$ term; its sign determines whether there is gain/loss
  - frequency difference cannot alter the gain/loss unless it can counter the large $k_a \cdot V_{\text{fluid}}$ term (e.g., $\pm 20$-Å UV)

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

\[
V_{\text{fluid}} \lim_{M \rightarrow c} \hat{r} = \eta = \frac{\Delta \omega - M \cos \theta_k}{|k_a| c_a}
\]

Matching conditions
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
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)

\[
\frac{I_1}{I_2} = \frac{dS_2}{dS_1} = \frac{n_1}{n_2} \exp \left\{ \int_{S_1} \frac{\nabla^2 \phi}{n} \, ds \right\} = \frac{n_1}{n_2} \exp \left\{ \int_{S_1} \frac{\nabla \cdot \{n \hat{s}\}}{n} \, ds \right\}
\]

- 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, $(\theta, \phi)$, which represent the angular coordinates.

- 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.
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: $150 \times 350 = 52.5$ kcells
- 3-D ASR: $20^3$ bins $\rightarrow 64$ kB per cell
- Memory for 3-D ASR:
  - single domain
    - DRACO ray trace
  - domain decomposed
    - DRACO 3-D ray trace on 128 cores

Absorbed laser power density (W/cm$^3$)

0.8
1.5
2.2
2.9

$z$ ($\mu$m)
0
500
1000
1500

$r$ ($\mu$m)
0
500
1000
1500
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
The symmetric-drive OMEGA shot 6000 is used to examine the basic CBET effect

- The shot achieves high intensities ($\sim 8 \times 10^{14} \text{ W/cm}^2$) to evaluate the effects of CBET

[Diagram showing CH and DD gas layers with dimensions and pressure, and a power-time graph with peak at 25.9 kJ]
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.

![Graph showing average deposit density vs. average radius for different values of ne'](image-url)
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

\[
\frac{dn_{\text{refr}}}{dt} = -\frac{1}{2} \frac{1}{n_{\text{refr}}} \frac{dn_e}{dt}, \text{ where } \begin{cases} 
>0; \text{ red shift} \\
<0; \text{ blue shift}
\end{cases}
\]

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:

\[
\left\langle \frac{dn_e'}{dt} \right\rangle = -\frac{1}{\text{vol}} \iiint \nabla \cdot [n_e' \nu_{\text{fluid}}] \, dv = -\frac{1}{\text{vol}} \iint \hat{n} \cdot [n_e' \nu_{\text{fluid}}] \, dA
\]

For a radial flow:

\[
\left\langle \frac{dn_e'}{dt} \right\rangle = n_e'_{2} \nu_{2} A_{2} - n_e'_{1} \nu_{1} A_{1}
\]
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, $n'_e \ll 0.1$, 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.

![Graph showing the balance of gradients and frequency chirp](image-url)
The rising edge of a pulse initiates a predicable sequence of Doppler-shift events

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

2) Next, a blue shift $\langle d n'_e / dt \rangle > 0$ 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, $\langle d n'_e / dt \rangle < 0$ as the negative density gradient steepens and moves inward
   - the volume expands and overwhelms the diminishing outward-propagating blue-shift region
As time progresses, the red-shift region expands, which eventually overwhelms the outer blue-shift region.
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
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 overdrives the target equator
Simulations predict that the shell changes from prolate to oblate when CBET is included.

- NIF shot N130128 observed this trend
Simulations with CBET improve the agreement with the measured trajectories x-ray framing camera (XRFC)
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
Absorption reduction caused by CBET can be mitigated in two different domains that can be combined

• 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 $\pm 6$-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.
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
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
Wavelength detuning has minimal impact in sidescatter mode in direct-drive targets

- 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)
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

NIF PD N130731, 4.2 ns
\{-1, 0, 1\} Å UV

Absorption intensity (W/cm²)

Polar angle (°)
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., $> \pm 2$-Å UV)
  - tailoring the spot shape will help limit the required $d\lambda_0$
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 $\lambda_0$
  - rays that pass over the equatorial region have increased absorption, even in Ring1
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
The majority of CBET occurs over the equatorial region in polar drive

- 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 $d\lambda_0$ of $\pm 6$-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 $\pm 6$-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 $\pm 6$-Å UV detuning

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

![Graph showing cumulative absorption fraction over time with different techniques.](chart.png)

- No CBET: 90%
- Detuning and modified spot shape: 76%
- Frequency detuning: 71%
- Modified spot shape: 65%
- CBET: 59%
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{imp}} ) (( \mu \text{m/\text{ns}} ))</td>
<td>367</td>
</tr>
<tr>
<td>CH thickness</td>
<td>39 nm</td>
</tr>
<tr>
<td>( \text{IFAR}_{\text{LLE}} )</td>
<td>24</td>
</tr>
<tr>
<td>In-flight ( \alpha )</td>
<td>2.2</td>
</tr>
<tr>
<td>Convergence ratio</td>
<td>30</td>
</tr>
<tr>
<td>Peak ( \rho R ) (g/cm(^2))</td>
<td>1.4</td>
</tr>
<tr>
<td>Fuel mass</td>
<td>1.34 mg</td>
</tr>
</tbody>
</table>

Flux-limited thermal transport

Nonlocal electron transport (no CBET) \( \rho \) (g/cm\(^3\))

TC11333
Hemispherical detuning simulations with nonlocal electron transport show the same trend as with $f = 0.06$

- While $\pm 2.5$-Å (UV) has too small an effect, $\pm 6$-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 $\pm 12$-Å UV case for reference)
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
The current $d\lambda_0$ option on the NIF does not allow for two different colors in each hemisphere.

- 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
North–south symmetry (spot location, \(\phi\) 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 \(d\theta\) shifts
- North–south asymmetry in polar repointing angles compensates for on-target shape changes caused by larger \(d\theta\)
NIF shot N130731 was used as the simulation’s basis for the $d\lambda_0$ CBET mitigation scheme using the current NIF configuration.

510-kJ pulse with foot and slow rise to flat top
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 $\sim 90 \, \mu m$.
Simulated self-emission images illustrate the predicted measurable effect of initial wavelength detuning tests

Wavelength detuning using NIF’s current configuration.

- CBET $d\lambda_0 = 0$
- CBET $d\lambda_0 \pm 3$-Å UV

$2 \times 520 \, \mu m$

Polar axis

$2 \times 440 \, \mu m$

$2 \times 430 \, \mu m$

$\pm 3$-Å $d\lambda_0$ yields $\sim 90$-μm $dR$ at the equator

- The change in shape caused by $d\lambda_0$ CBET mitigation enhances equatorial drive as predicted; $dR \sim 90\mu m$
The near-backscatter imaging plates are positioned to detect the changes.

Wavelength detuning using NIF’s current configuration

$t = 6.7$ ns

CBET $d\lambda_0 = 0$
Scattered-light diagnostic

CBET $d\lambda_0 \pm 3$-Å UV
Scattered-light diagnostic

Scattered light ($J/cm^2$)

- 2.972
- 1.508
- 1.765
- 0.388
- 0.197
- 0.100
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.