Inline Modeling of Cross-Beam Energy Transfer and Backscatter in Hohlraums

Lawrence Livermore National Lab

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Cross-beam energy transfer (CBET) is needed for round implosions in gas-filled hohlraums

- Transfer to beam with lower frequency in plasma rest frame
- Determined by plasma flow and laser wavelengths
- NIF: 3 wavelengths (“colors”) for 23°, 30°, and outer cones
- Round implosions need transfer to inners: $\lambda_{\text{in}} - \lambda_{\text{out}} \sim 5-10 \text{ Å} @ 1\omega$ on cryo gas-filled shots
Summary: Hydra\textsuperscript{1} inline CBET model is applied to gas-filled NIF hohlraums with large transfer

- **Script process:**
  - Straight rays, no inverse brem. absorption, used to date for NIF designs
  - Gives more CBET than experiments -> $\delta n$ saturation clamp

- **Inline model\textsuperscript{2}:** Hydra calculates CBET every time step
  - Same linear, kinetic coupled-mode equations as script

- **Inline model advantages vs. script:**
  - One Hydra run, not two
  - More physics: refraction, inverse brem. absorption, spatially non-uniform transfer
  - Ion wave energy and momentum deposition:
    May limit CBET\textsuperscript{4}, reduce need for $\delta n$ saturation clamp

\textsuperscript{1}M. M. Marinak et al., PoP 2001; \textsuperscript{2}M. M. Marinak et al., APS-DPP 2012
\textsuperscript{3} P. Michel et al., PoP 2010; \textsuperscript{4}P. Michel et al., PRL 2012
Physics results

• Early-time picket:
  — Inline model agrees with script, once inners burn through LEH plasma
  — Before, plasma dense and cold, inverse bremsstrahlung (neglected by CBET script) matters

• Peak power:
  — Inline model converges to script result – with enough numerical rays
  — Inline ion-wave energy deposition heats LEH ions, little effect on transfer

NIF shot N131118:
Laser Power vs. Time
CBET model uses coupled-mode equations for unpolarized beams: NIF quad-to-quad transfer

\[
\frac{dI_1}{dz} = g \cdot \min \left[ I_0 I_1, a \delta n_{\text{max}} \sqrt{I_0 I_1} \right] \quad g = \text{coupling coeff}
\]

\[
\frac{dI_0}{dz} = -\frac{\omega_0}{\omega_1} \frac{dI_1}{dz} \quad \text{Manley-Rowe}
\]

Laser polarization angles random and uncorrelated
CBET w/ polarized beams: P. Michel, talk PO4.13 Wed. PM

\[
\delta n \propto \min \left[ \sqrt{I_0 I_1}, \delta n_{\text{max}} \right]
\]

\[
K = \frac{\chi_e (1 + \chi_i)}{1 + \chi_e + \chi_i}
\]

- Strongly damped ion waves
- Saturation clamp \( \delta n_{\text{max}} \)

Uses kinetic Z - function at
ion wave \((\omega, k) = (\omega_0 - \omega_1, k_0 - k_1)\)

Ion-wave momentum and energy deposition:

\[
m_i \frac{d\langle \vec{v}_i \rangle}{dt} = -\alpha \vec{k}
\]

\[
\frac{dT_i}{dt} = \frac{2}{3} \left( \omega - \vec{k} \cdot \langle \vec{v}_i \rangle \right) \alpha
\]

\[
\alpha = \frac{|E_k|^2 \text{Im} \chi_i}{8\pi n_i}
\]

P. Michel et al., PRL 2012
CBET along HYDRA ray found using zonal intensity: sum of all rays in a zone

In HYDRA, rays carry power, intensity is a zonal quantity

- Transfer is done along rays, based on zonal intensity
- Enough numerical rays needed to resolve intensity
- Manley-Rowe not exactly satisfied
- Numerically iterate until CBET power loss < tolerance * incident power
Picket: inline model gives less transfer than script

Before 1 ns:
- Inline model gives less transfer
- Inners absorbed in dense, cold LEH plasma
- X-ray flux symmetry on capsule similar

After 1 ns:
- Inners propagate through LEH
- Script and inline model agree

Cone fraction = Inner / total power

- Generic low-foot pulse
- Moderate CBET: \( \lambda_{in} - \lambda_{out} = 3.5 \, \text{Å} \)
- Saturation clamp \( \delta n_e/n_e = 6 \times 10^{-4} \)
Peak power: inline CBET converges to script results with more numerical rays: intensity better resolved

Peak power cone fraction vs time

Inline rays per quad:
- 1200
- 900
- 600
- 300

- Generic low-foot pulse
- Moderate CBET: \( \lambda_\text{in} - \lambda_\text{out} = 3.5 \text{ Å} \)
- Saturation clamp \( \delta n_e/n_e = 6 \times 10^{-4} \)

Inline cone fraction converges to script

Script with plasma maps from:
- **Black**: no CBET
- **Green**: inline 1200 rays

- **Magenta** and **green** curves agree: Script and inline model give same transfer on same plasma maps
- **Black** and **green** curves agree: Script gives same transfer on plasma maps with and without CBET: no need to iterate script
Peak power: inline ion-wave energy deposition has little effect on transfer

N131118: high-foot 2D ConA
$E_{\text{laser}} = 1.71 \text{ MJ}$
$(\lambda_{23}, \lambda_{30}) - \lambda_{\text{out}} = (8.2, 7.5) \text{ Å @ } 1\omega$
CH capsule, He gas fill
Saturation clamp $\delta n_e/n_e = 10^{-3}$

3-shock Laser pulse

Cone fraction:
inner / total power

3-shock Laser pulse

Cone fraction: inline CBET with IAW dep.

Saturation clamp $\delta n_e/n_e = 10^{-3}$

Inline CBET w/o IAW deposition
Peak power: CBET without ion deposition changes ion temperature via cone fraction

T_{ion} [keV] @ 14 ns:
late peak power

<table>
<thead>
<tr>
<th>No CBET</th>
<th>Inline CBET, no ion-wave deposition</th>
</tr>
</thead>
</table>

CBET – No CBET

Au bubble cooler

Inner spots hotter
Peak power: CBET with ion-wave deposition heats LEH ions – little effect on transfer

<table>
<thead>
<tr>
<th>Inline CBET $T_{ion}$ [keV] @ 14 ns: late peak power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without ion-wave deposition</td>
</tr>
<tr>
<td>Wall</td>
</tr>
<tr>
<td>LEH</td>
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**High-foot shot N131118**

<table>
<thead>
<tr>
<th>$T_{ion}$ [keV]</th>
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<tbody>
<tr>
<td>IAW dep – No IAW dep</td>
</tr>
<tr>
<td>200 eV</td>
</tr>
<tr>
<td>400 eV</td>
</tr>
<tr>
<td>600 eV</td>
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<tr>
<td>700 eV</td>
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</tbody>
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Hydra inline CBET model works, being extended to include Raman backscatter

- Picket: Inline model agrees with script once inners burn through LEH
- Peak power:
  - Inline model agrees with script, with enough numerical rays
  - Inline ion-wave energy deposition has little effect on transfer
- Backscatter also heats LEH, impairs inner-beam propagation more than reducing incident laser power
- Similar inline models under development in Lasnex (D. Bailey)
• BACKUP
• BELOW
• HERE
Picket: script and inline models both give large CBET, differ in details

Incident power:
Inners burn through window to avoid hot electrons

Cone fraction:
inner / total power

inline CBET results: curves overlap
blue: no IAW deposition
dashed magenta: yes IAW dep.
Peak power: x-ray flux moments on capsule behave like cone fraction, inline converges to script

- 2D ConA shots and hot-spot self-emission measure capsule P2/P0 to < 5%
- P2/P0 <~ 2% in peak required for ignition (A. Kritcher)
Details of model as run for this talk

• Exponential model with Manley-Rowe cap:

\[
\frac{dI_1}{dz} = GI_1 \quad G \propto I_0 \quad \rightarrow \quad P_{\text{ray},1}(\text{end}) = P_{\text{ray},1}(\text{begin}) \exp[G]
\]

— Intensity of other beam updated separately: pump depletion occurs over numerical iterations
— Manley-Rowe cap: ray can’t gain more power than available from all beams transferring to it

• Beam k vector found by intensity-weighting rays in a zone: can change from value at lens due to refraction

• Numerically iterate, max of 10 times, til power lost due to CBET (Manley-Rowe violation) < $10^{-4}$ * incident power
Cone fraction:
inner / total power

CBET script

inline CBET results:
blue: no IAW deposition
dashed magenta: yes IAW dep.

Incident c.f.

Total power

cone fraction: inner / total pow.

1.0
0.5
0.0

time [ns]

10 12 14
The 4 C’s of coding

• Correctness – are the desired equations being solved?
  — Yes: comparisons with Python coupled-mode solutions (S. Sepke)
• Crash? Model runs without crashing
• Conservation – is power error acceptable? Yes
• Convergence – do physical answers like flux moments and capsule shape change with numerics, e.g. zoning, rays?

CBET loss / incident power

Number of rays per quad:
300 [current default] 600 900 1200

Specified tolerance of $10^{-4}$ almost always achieved, with $\leq 10$ iterations
The inline Hydra model includes effects beyond the offline script

CBET script method (P. Michel):
• Hydra “pre-transfer” run: no CBET, no backscatter, no drive multipliers
• CBET script run on pre-transfer plasma conditions
• Hydra “post-transfer” run with incident cone powers modified according to script

Additional physics in inline CBET model:
• Inverse brem. absorption
• Ray refraction
• Spatially non-uniform transfer: both along beam propagation direction and transverse to it
• Momentum and energy deposition by CBET-driven ion waves, may limit CBET\(^1\): under development

• Inline model only uses a single Hydra run, with increased computer resources for laser propagation

\(^1\)P. Michel et al., PRL 109, 195004 (2012)
\[ I = \sum_{r=1}^{N_{\text{rays}}} P_r \frac{s_r}{\Delta V}, \quad P_r = \frac{1}{s_r} \int_0^{s_r} ds' P(s') \]

\[ s_r = \text{distance of ray through zone} \]

Coupling coeff from formula page:
\[ \frac{\pi r_e}{2 \omega_0 m_e c^2} \frac{k^2}{k_0 k_1} [1 + \cos^2(\psi)] \text{Im}(K) \]
111: Script gives slightly less transfer than Re-emit shot data 1

1E. L. Dewald, J. L. Milovich et al., PRL 2013