Modeling Laser-Plasma Interaction over a Suite of NIF Experiments


APS DPP 2017
23 October 2017
Laser-Plasma Interaction (LPI) in hohlraums

Important for high hohlraum fill density
Low-foot, high-foot designs

- **Cross-Beam Energy Transfer (CBET):** $\Delta \lambda$
  - Form of Brillouin scattering
  - Laser 1 $\gamma \rightarrow$ Laser 2 $\gamma$ + ion acoustic wave
  - To longer wavelength laser in plasma frame

- **Stimulated Raman scattering (SRS):**
  - Laser $\gamma \rightarrow$ scattered $\gamma$ + Langmuir wave
  - Energy lost
  - Energetic or “hot” electrons $\rightarrow$ preheat
  - Also affect shape

- **Stimulated Brillouin scattering (SBS):**
  - Laser $\gamma \rightarrow$ scattered $\gamma$ + ion acoustic wave

“Inline” LPI models recently added to HYDRA and LASNEX:
LPI scaling study: understand and model trends in NIF LPI data

Nirvana: universal “fruit plot”: simulated LPI figure of merit collapses data from different targets

Measured LPI

Simulated LPI (e.g. linear gain, pF3D reflectivity)
Summary: towards predictive rad-hydro + laser-plasma modeling

Lasnex rad-hydro model: O. Jones et al., PoP 2017
- Converged numerics
- No per-shot multipliers
- DCA non-LTE model
- Low electron flux limit $f = 0.03$
- **New:** Inline CBET: clamp $\delta n_e/n_e = 0.01$

NIF “bigfoot” shot [C. Thomas, APS-DPP 2016]
- CBET (calculated) to outer cones
- Outer-cone SBS: 10-15% end of pulse

Outer SBS modeling
- **DEPLETE:** ray-based extension of linear gain
- **pF3D:** paraxial-envelope code
  - speckles, polarization smoothing, SSD, ...
- SBS Increases with time, but less than data
- SBS from gold bubble
Energetics across a set of NIF shots

“Drive deficit”
- Rad-hydro modeling generally over-predicts x-ray drive in NIF hohlraums
- Especially for long pulses, high gas fill density, high backscatter

![Graph showing measured vs simulated x-ray bangtime](image)

- Bigfoot DT: HDC, 0.3 mg/cc
- HDC DT: 0.3 mg/cc
- HDC gas- scan 0.6 mg/cc
- HDC gas- scan 1.6 mg/cc: Long coast time, Higher SRS
- Lasnex x-ray drive > measured
LPI simulated for “Bigfoot”\textsuperscript{1} shot N170109

**Bigfoot**

- 1st and 2\textsuperscript{nd} shocks merge in ablator, before reaching DT fuel
- “Robust” hostspot: high adiabat, high rho*R
- Less prone to hydro instabilities
- Price: lower 1D fusion gain

\[ \Delta \lambda = 0: \text{CBET due to plasma flow only} \]

**Outer beams: “Quad splitting”**

- Spread out outer beam spots on wall
- 4 beams in an outer quad split in azimuth
- 44’s and 50’s separated in Z

**Benefits:**

- Less azimuthal asymmetry
- Lower intensity at wall $\rightarrow$ lower SBS
- Less M-band x-rays
- Less wall / bubble motion

\textsuperscript{1}C. A. Thomas, APS DPP 2016 invited talk
Bigfoot shot N170109: SBS late in time on cone 50

Q31B FABS: Inner cone, 30°

![Graph showing Power vs Time for Q31B FABS: Inner cone, 30°](image)

Incident
SBS
SRS

Time (ns)

DrD (Drive diagnostic) sensors
SBS in >= one beam on every quad:
• More SBS on cone 50 than 44

Q36B FABS: Outer cone, 50°

![Graph showing Power vs Time for Q36B FABS: Outer cone, 50°](image)

SBS
SRS

Time (ns)

Cone: 23, 30, 44, 50

![Graph showing SBS Power at LEH (TW/beam)](image)

noise
Bigfoot: calculated CBET to outers, especially 50’s

Net transfer to each cone

Cone fraction = Inner / Total power

cone 50: transfer FROM all other cones

CBET may be part of reason SBS higher on cone 50 than cone 44

NIF Shot N170109
Bigfoot: Cone 50 SBS spectrum vs. DEPLETE

- DEPLETE spectrum redshifted by ~ 2 Ang. vs data
- Depends on sound speed and flow velocity
- Neglects SSD bandwidth, “Dewandre effect:” wavelength shift from $\partial n_e / \partial t$

DEPLETE: Cone 50 SBS develops in gold bubble

Laser light

Background: \(n_e/n_{\text{crit}}\)

SBS light, \(\Delta \lambda = 0\) Ang.

SBS light, \(\Delta \lambda = 2\) Ang.

N170109

5.75 ns: late peak power

Au wall

Laser intensity [a.u.]

SBS intensity / noise [log scale]
Cone 50 SBS: Measured and DEPLETE reflectivities qualitatively track vs. time

Deplete reflectivity: sum over rays of wavelength-integrated SBS intensity
Cone 50 SBS: pF3D$^2$ simulations close to measured reflectivity, when CBET included

NIF bigfoot shot N170109

pF3D simulations by R. L. Berger

\[\text{SBS reflectivity [%]} \]

\[\text{time [ns]} \]

Measured

pF3D with calculated CBET included

pF3D with Incident power

pF3D: outer SBS grows in gold bubble

- pF3D run includes one 48° and one 52° beam – each orthogonally polarized
- 50° quad has two other beams: spatially separated at wall due to “quad splitting”
- Plots in pF3D coordinates: laser propagates in z
LPI scaling study: status and future work

LPI on “Bigfoot” shot N170109
- CBET modeling: CBET to outers, increases in time
- Backscatter: mostly cone 50 SBS, peaks late in time
- Cone 50 SBS modeling: DEPLETE and pF3D
  - Similar reflectivity to data, when CBET included

Future work
- Apply to more shots, more LPI data – inner SRS, SBS in beams within quad
- Suggest rad-hydro and LPI modeling improvements, e.g. gold bubble

Graphs showing cone 50 SBS reflectivity over time, measured versus simulated, and a goal of a "fruit plot" with different materials and fill levels.
BACKUP BELOW
**LPI a key and varying player on NIF ignition shots**

<table>
<thead>
<tr>
<th>CH ablator campaigns long pulse 15-25 ns</th>
<th>low foot ‘09-12 low adiabat</th>
<th>high foot 12-14 higher adiabat</th>
<th>CH672 14-now large scale 672 hohlraum</th>
</tr>
</thead>
<tbody>
<tr>
<td>hohlraum He fill, mg/cc</td>
<td>0.96</td>
<td>1.6</td>
<td>0.6</td>
</tr>
<tr>
<td>CBET: $\Delta \lambda = \lambda_{\text{in}} - \lambda_{\text{out}}$</td>
<td>high (to inners)</td>
<td>high (to inners)</td>
<td>0 usually</td>
</tr>
<tr>
<td>Inner BS</td>
<td>high SRS</td>
<td>high SRS</td>
<td>moderate SRS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SBS with $\Delta \lambda$: mirror damage</td>
</tr>
<tr>
<td>Outer BS</td>
<td>low</td>
<td>low</td>
<td>SBS throughout peak</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HDC ablator campaigns short pulse 5-9 ns</th>
<th>near-vacuum hohlraum 12-15 symmetry dynamic, hard</th>
<th>bigfoot + HDC 15-now</th>
</tr>
</thead>
<tbody>
<tr>
<td>hohlraum He fill, mg/cc</td>
<td>0.032</td>
<td>0.3</td>
</tr>
<tr>
<td>CBET: $\Delta \lambda = \lambda_{\text{in}} - \lambda_{\text{out}}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Inner BS</td>
<td>low</td>
<td>modest SRS</td>
</tr>
<tr>
<td>Outer BS</td>
<td>low</td>
<td>high SBS at end of long pulse</td>
</tr>
</tbody>
</table>

**Be campaigns intermediate pulse**

- **Be high foot 12-14**
  - Analogous to CH high foot
  - LPI similar

- **Be672 15-now**
  - similar to CH672
  - LPI similar, somewhat lower
LPI modeling: two-step process

Rad-hydro code
- Hydra, Lasnex
- Inline models (CBET, SRS)

LPI code
- NEWLIP: linear gains
- DEPLETE: extended gains
- CBET script (P. Michel)
- New ray-based tool (A. Colaitis)
- pF3D: paraxial-envelope, speckles
- SLIP: steady-state pF3D

plasma maps
low-density conditions
\( n_e < n_{\text{crit}} = 9 \times 10^{21} \text{ /cm}^3 \)

Validated LPI model can guide future designs:
- Current “hybrid” campaigns
- Innovative hohlraum concepts
  - Foam liners, new geometries
- 2-2.5 MJ blue-light NIF
- 3 MJ green-light NIF
- Imposed B field
Rad-hydro model: “best current” physics in Lasnex\textsuperscript{1}

- **Opacity + EOS**
  - LTE tables for $T_e < T_{\text{crit}}$, non-LTE DCA for $T_e > T_{\text{crit}}$
  - $T_{\text{crit}} = 300$ eV in wall, 50 eV elsewhere (capsule)
  - DCA models: March 2014
  - Gold: dca\_79x5 – improved “bubble” physics

- **Laser**
  - No inline SRS/SBS
    - Backscatter removed from incident laser
  - Inline CBET: unpolarized quads
    - Saturation $\delta n_e/n_e = 0.01$
  - Inverse brems. with Langdon effect
  - Ponderomotive force: needed for CBET momentum deposition

- **Electron heat conduction**
  - Heat flux $q = \min(q_{\text{SH}}, f n_e T_e v_{Te})$
  - $q_{\text{SH}} = \text{Spitzer-Harm} + \text{Lee-More corrections}$
  - Low flux limit $f = 0.03$ everywhere
  - No MHD, nonlocal, ion turbulence models

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\textsuperscript{1}O. Jones et al., Phys. Plasmas 2017

Simulations: too much x-ray drive, esp. for long pulses, high fill density

2D RZ, Only bottom half: BS diagnostics there

FABS, NBI detectors
Rad-hydro: high-resolution numerics, ALE mesh

• **Numerical resolution**: O. Jones’ ”hi-res” settings from convergence study
  - Capsule: 72 angular zones in 90° → Δθ = 1.25°
  - Wall: innermost zone Δr=4 nm, Δr increases by 1.03x
  - 180 radiation energy groups
  - 10 zones across LEH window thickness

• **Mesh**: “As Lagrangian As Reasonably Achievable”*  
  - ALE (Arbitrary Lagrangian-Eulerian) mesh management: R. Tipton
  - Hohlraum: ALE from t=0, may freeze mesh after laser is off
  - Capsule: ALE from user-determined t>0, mesh not frozen

• **Laser**: 600 rays per quad, CBET iteration options

• **LHT (Lasnex Hohlraum Template)** git version-controlled input deck  
  - Needed to handle multiple shots + multiple designers
  - Based on deck from Cliff Thomas, from Richard Town, Peter Amendt, etc.
  - No ad-hoc / per-shot multipliers: power, cone fraction, ...
  - Same Lasnex version: 13 April 2017

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1O. Jones et al., Phys. Plasmas 2017

*N. Meezan, private communication (2007)*
Computing resources pretty modest for high-resolution hohlraum simulation

Lasnex run of N170109 bigfoot DT shot
- 170807 code – several fixes / improvements
- 2 nodes of mica: 72 TOSS_3 cores
- One-sided hohlraum
- Laser: 14,400 rays, inline CBET
- DCA: dca_79x6 (results in talk use x5): 3923 levels
- Hi res: zones: 32k gold, 20k others

On 72 CPUs:
15 hours to laser off
10 more hours to bang

<table>
<thead>
<tr>
<th>time</th>
<th>6.5 ns: laser off</th>
<th>7.1 ns: just after x-ray bangtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall-hours := wh</td>
<td>14.9</td>
<td>25.0</td>
</tr>
<tr>
<td>CPU-hours (wh*72)</td>
<td>1073</td>
<td>1800</td>
</tr>
<tr>
<td>DCA [%wh]</td>
<td>32</td>
<td>48</td>
</tr>
<tr>
<td>laser [%wh]</td>
<td>38</td>
<td>24</td>
</tr>
<tr>
<td>other [%wh]</td>
<td>31</td>
<td>28</td>
</tr>
</tbody>
</table>

Hats off to Lasnex team, esp. D. Bailey, G. Zimmerman, J. Harte
DEPLETE\textsuperscript{1}: ray-based, steady-state backscatter calculations, extension of linear gain

\[ \frac{d}{dz} I_0(z) = -\kappa_0 I_0 - I_0 \int d\omega_1 \frac{\omega_0}{\omega_1} (\tau_1 + \Gamma_1 i_1) \]

\[ - \frac{\partial}{\partial z} i_1(z, \omega_1) = -\kappa_1 i_1 - \Sigma_1 - I_0 (\tau_1 + \Gamma_1 i_1) \]

Features of DEPLETE:
- Uses 1-D plasma conditions from 3-D ray-trace
- Spectrum of scattered frequencies
- Strong damping limit for plasma waves
- Pump depletion of laser
- Linear kinetic coupling coefficients
- Collisional plasma-wave damping

DEPLETE lacks:
- Temporal effects
- Laser speckles
- PS, SSD
- Dewandre effect
- Multi-D effects, e.g. refractive intensification

\[ G = \ln \frac{i_1(\omega, z_0)}{i_1^{\text{brem}}(\omega, z_0)} \]

noise level without laser = scattered light with just brem. emission + absorption

Each ray has narrow SBS resonance at different wavelength\textsuperscript{1}

\textsuperscript{1}L. Tolstoy, *Anna Karenina* (1878)
Ion waves weakly damped for \( Z T_e / T_i \gg 1 \): e.g. gold

**IAW Landau damping rate: gold**

\[ T_e = 2 T_i, \quad k \lambda_{De} = 0.6 \]

\[ \frac{\nu}{\omega} \propto \left( \frac{Z m_e}{m_i} \right)^{\frac{1}{2}} \exp \left[ - \frac{Z m_e}{2 m_i} \right] + \frac{1}{2} \left( \frac{Z T_e}{T_i} \right)^{\frac{3}{2}} \exp \left[ - \frac{Z T_e}{2 T_i} \right] \]

**SBS spectrum**

~1/\( \nu \)  

\( \sim \nu \)

Electrons  

Ions  

plus collisions (not included)