LPI experiments with single and multiple NIF beams

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D. J. Strozzi, J. D. Moody, H. F. Robey, L. Divol, P. Michel,
R. L. Berger, E. A. Williams, D. E. Hinkel

Lawrence Livermore National Lab
N120106 and N120115: “keyhole” shots isolate effect of outer cones on inners

- “Keyhole” targets: VISAR detector: tune first 3 shocks
- “Fast rise” (~1 ns) from third to fourth shocks
- Gold hohlraum with “large” laser entrance hole (LEH)
- 3 laser colors: \( \lambda_{30} - \lambda_{\text{out}} = 6.6 \text{ Ang.} \), \( \lambda_{23} - \lambda_{30} = 1.5 \text{ Ang.} \)
- Same energy, except outers extended in N120115
- Very low inner-cone SBS

Fourth pulse fast-rise (N120106)

Window for LPI experiments! VISAR doesn’t give shock data this late
N120106: SRS on both inner cones drops whenouters turn off

30° quad

23° quad

Power (TW)

Time (ns)
SRS spectrum on 30° cone evolves similarly if outers truncated or not; gain spectrum within ~10 nm

Gain spectrum from Hydra rad-hydro by H. Robey with high-flux model; low-flux model gives 20-30 nm longer wavelength
N1201{06, 15}: SRS power when outers are off is 40% of value with outers on

SRS data for $30^\circ$ cone

30° cone SRS power: N120106 (outers off) / N120115 (outers on): 0.4
Inner SRS drops when outers off: no power transfer, no re-amplification, less saturation

SRS power *not* reflectivity

Reflectivity

Tang:
- R incr. w/ intensity
- linear SRS
- re-amplification
- hard:
  - R indep. of Intensity

SRS Gain = g*intensity

When outers off:
- Decreases because transfer stops
- Decreases if Tang (not hard) saturated
- Decreases because re-amplification stops

Two unknowns: \( f_{\text{out}} \), \( G_{\text{re-amp}} \)

SRS light from one beam amplified when crossing another beam [P. Michel et al.]
One-parameter model for cross-beam energy transfer from outer to inner cones

\[ P_{23,30} = P_{23,30}^{inc} + \frac{1}{2} \Delta P_{out} \]

\[ \Delta P_{out} = \text{total power xfer from outer to inner cones} \]

\[ P_{out}^{inc} = P_{44}^{inc} + P_{50}^{inc} \approx 4P_{30}^{inc} \]

\[ P_{23,30} = P_{23,30}^{inc}(1 + 2f_{out}) \]

\[ f_{out} = \text{fraction of outer-cone power transferred to inner cones} \]

We neglect spatial non-uniformity in transfer, which should be looked at (R. L. Berger)
Measured ratio of SRS powers relates transfer and re-amplification

\[ \frac{P_{SRS}^{\text{on}}}{P_{SRS}^{\text{off}}} = \rho \cdot (1 + 2f_{\text{out}}) \exp \left( \frac{G_{\text{re-amp}}}{R(g \cdot I_{30}^{\text{on}})} \right) \]

\[ \rho = \frac{R(g \cdot I_{30}^{\text{on}})}{R(g \cdot I_{30}^{\text{off}})} \to 1 \]

Hard saturation: maximizes \( G_{\text{re-amp}} \)

- \( f_{\text{out}} \approx 0.35 \) agrees w/ capsule symmetry data (R. Town)
- Hydra’s \( f_{\text{out}} \) passes basic check: inconsistent w/ SRS drop if \( f_{\text{out}} > G_{\text{re-amp}} = 0 \) values

\( f_{\text{out}} = 0.35 \)

\( P_{SRS}^{\text{off}} / P_{SRS}^{\text{on}} = 0.4 \) N120106 30° cone

\( f_{\text{out}} = \text{frac. of outer power xferred} \)
Allow for saturation to vary with intensity

- \(G_{\text{re-amp}} = 0\): SRS changes only due to power transfer; \(G_{\text{re-amp}} > 0\) lowers A, raises G
- Neglect change in \(g\) = role of plasma conditions in gain
  — measured spectra similar for N120106 and N120115

\[
A \equiv e^{-G_{\text{re-amp}}} \frac{P_{\text{on}}}{P_{\text{off}}} = \rho (1 + 2f_{\text{out}}) = \alpha(f_{\text{out}}, G)
\]

\[
\rho = \frac{R(P_{30}^{\text{on}})}{R(P_{30}^{\text{off}})} = \frac{R(G \cdot (1 + 2f_{\text{out}}))}{R(G)}
\]

\[
G \equiv gI_{30}^{\text{inc}}
\]

Tang formula:
coupled-mode eqs. w/ pump depletion

\[
\tilde{R} (1 - \tilde{R} + \tilde{s}) = \tilde{s} \exp \left[ G \left(1 - \tilde{R} \right) \right]
\]

\[
\tilde{R} = \frac{\omega_0}{\omega_1} \tilde{R}, \quad \tilde{s} = \frac{\omega_0}{\omega_1} \frac{I_{\text{1seed}}}{I_0} \rightarrow 10^{-9}
\]

linear theory

\[
R = s \exp G; \quad G = \frac{1}{2f} \ln \left[ \frac{A}{1 + 2f} \right]
\]
Inner-cone SRS is strongly saturated

- Small drop in SRS for large transfer:
  - Linear branch requires small gain, not consistent w/ large SRS
  - Consistent w/ large gain on strongly-saturated, pump-depleted Tang branch

- Estimating G and $f_{out}$:
  - N120106: SRS power ~ 28% incident when outers off; wavelength = 570 nm
  - No re-absorption of scattered light: $R_{\tilde{t}} = 0.45$, $G = 35$ -> $f_{out} = 0.33$ – near sims!
  - $R_{off} / R_{on} = 0.45 / 0.67 = 0.67$; $I*dR/dI = 0.2$
Conclusions for N120106 and N120115: effect of outer cones on inners

- Inner cone SRS power approximately **doubled** by presence of outer cones
- Hydra modeling, and symmetry scaling with $\Delta \lambda$, suggest 35% of outer beam power transferred at time outers shut off
- Measured SRS decrease consistent with this 35% transfer, and with modest outer-inner re-amplification gain exponent of at most 0.15 - 0.4
- Saturation: neglecting re-amp. (which *minimizes* saturated gain): {large SRS, large transfer, and small SRS drop when outers} imply SRS is strongly saturated, not in linear regime
March keyholes: one inner cone extended – “single-quad” LPI experiments!

- But in a rapidly evolving, maybe azimuthally-asymmetric, hohlraum…
- Slow (3 ns) rise of fourth pulse
- “small” LEH
- 3-color scheme: $\lambda_{30} - \lambda_{\text{out}} = 7.3$ Ang.; $\lambda_{23} - \lambda_{30} = 1.2$ Ang.
- Single-quad expt. if no re-amplification of one inner quad by others on same cone
  — Power transfer excluded by azimuthal symmetry

<table>
<thead>
<tr>
<th>shot</th>
<th>hohlraum</th>
<th>peak power [TW]</th>
<th>extended cone</th>
</tr>
</thead>
<tbody>
<tr>
<td>N120229</td>
<td>DU</td>
<td>420</td>
<td>30</td>
</tr>
<tr>
<td>N120303</td>
<td>DU</td>
<td>420</td>
<td>23</td>
</tr>
<tr>
<td>N120304</td>
<td>Au</td>
<td>420</td>
<td>30</td>
</tr>
<tr>
<td>N120305</td>
<td>DU</td>
<td>320</td>
<td>30</td>
</tr>
</tbody>
</table>

Shot we study
N120305: “single-quad” 30° cone SRS ~ 15-20%
N120305: SRS spectrum on 30° cone

FABS spectrum

\[ \lambda \text{ of max. signal} \]

20.3 ns

19.8 ns

gain spectrum

SRS time history

FABS a.u. gain

peak gain

wavelength [nm]
N120305: 30° cone SRS: FABS and linear gain agree when all cones on, differ when just cone 30 on

FABS spectrum

zoomed late, and capped

max FABS
max gain < 580 nm
SRS power

Multi-quad effects not essential to match spectrum
N120305: 30° cone SRS FABS spectrum: filling and cooling rates

SRS matching conditions: $\lambda$, $T_e \rightarrow n_e$

<table>
<thead>
<tr>
<th>t [ns]</th>
<th>$\lambda$ [nm]</th>
<th>$n_e/n_{cr}$ [1.5 keV]</th>
<th>$n_e/n_{cr}$ [3 keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>545</td>
<td>0.102</td>
<td>0.069</td>
</tr>
<tr>
<td>19.5</td>
<td>558</td>
<td>0.115</td>
<td>0.082</td>
</tr>
</tbody>
</table>

fill rate: $dn_e/dt = 0.026 \, n_{cr}/ns$ for 1.5 or 3 keV!

cooling rate: $0.1n_{cr}$ and 2.3 keV match with 560 nm. To keep wavelength constant, $dn_e/dt = 0.026$ is balanced by $dT_e/dt = -1.1$ keV/ns
N120305: 30° cone SRS: what happens when other cones turn off

**SRS gain, \( t = 20.3 \) ns**

- FABS wavelength of 560 nm in “dead zone” of gain spectrum:
  - LPI physics (speckles, inflation) not likely to fix that
  - Plasma conditions likely wrong

**Why gains blueshifted at late time?**
- Azimuthal non-uniformity:
  - Plasma really hotter in beams?
- Rad-hydro codes have trouble when laser turned off?
N120305: SBS on 30° cone: gains ~ 1.5 Ang. redshifted vs. measurement

Time-dependent $n_e^1$ may explain redshift [R. L. Berger]

N120305: plasma maps from H. Robey’s R-Z post-shot Hydra runs

20.3 ns (just 30’s on) - 19.8 ns (other cones start turning off) = difference

$\frac{n_e}{n_{cr}}$

$T_e [\text{keV}]$

~1 keV / ns for inners: close to estimate
Conclusions on March 2012 keyholes

• Measured single-quad inner-cone SRS ~ 15-20%

• When all cones on, single-quad gain spectrum close to data
  — multi-quad effects not essential

• Gain spectrum changes more when just 30’s are on than data –
  — rad-hydro plasma conditions likely wrong, perhaps due to degraded drive

• SBS gain spectrum ~ 1.5 Ang. redshifted vs. data
  — time-dependent density may explain