Understanding Raman Scattering in NIF Ignition Experiments


*Lawrence Livermore National Lab*

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Linear gain analyses better match reflectivity trends with improved plasma and laser beam models

- **“High Flux Model” (HFM)** for rad-hydro:
  - DCA opacities, 0.15 electron heat flux limiter
  - Cross-beam energy transfer (linear model with clamp)
  - Measured backscatter removed

- **Linear gain spectrum** with HFM plasma conditions:
  - Close to measured SRS wavelength
  - Agreement better if multi-quad (overlapped beam) laser intensity used, rather than single-quad

- **Gain and reflectivity time histories:**
  - Gain increases in time, while reflectivity first increases and then decreases late in peak power

- **Spatially non-uniform cross-beam energy transfer:**
  - Gain decreases late in peak power, like measured reflectivity

- **Electron trapping:** pF3D simulations give SRS Langmuir waves above threshold for trapping nonlinearities
We study NIF shot N110214 - symmetry capsule (symcap) with \( \sim 1.3 \) MJ laser energy - 30° (inner) cone

- “Post-transfer” reflectivity = measured SRS / Lasnex power w/ cross-beam transfer.

- SRS energy reflectivity [joules out / joules in]:
  - Incident power: 27%
  - Post-transfer power: 19%

Power on one quad [TW]

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<th>post-transfer power</th>
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<th>post-transfer power</th>
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<th>SRS reflectivity: nominal, post-transfer</th>
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DJS: AA SRS 2011; p. 3
SRS wavelength increases in time, indicating SRS occurs at progressively higher density.

Measured SRS FABS spectrum N110214

- *Suggested by L. Suter*

FABS = full aperture backscatter station
NBI = near-backscatter imager

Drop in FABS signal due to motion of SRS light out of detector – total (FABS+NBI) SRS doesn’t drop.

[J. Moody, prior talk]
With HFM (high-flux model), wavelength of peak multi-quad gain agrees well with FABS, indicating plasma conditions are ~ right

- Wavelength of max SRS separates power history from plasma conditions.

- Early peak power: 17-18ns:
  - Single-quad gains peak at a longer wavelength.
  - FABS signal reduced due to motion of SRS.
  - longer wavelengths refract more, so FABS light may be shorter wavelength than total SRS light.
Multi-quad SRS gains peak at shorter wavelength since beams overlap near laser entrance hole.

Multi-quad SRS gains peak at shorter wavelength than single-quad gains: beams overlap more near the LEH, where the electron density, and plasma frequency, is lower.
Spatially uniform transfer: reflectivity scales with gain until late in peak power

- Gain tracks reflectivity until ~ 18.5 ns (mid-late peak power).
- At late time, reflectivity drops but gain doesn’t.
- Late-time gain coming from long wavelengths - generally not observed in FABS.
More detailed calculations of cross-beam transfer introduce spatial non-uniformity in the intensities

- Current HFM: distributes transferred power uniformly across the beam
- Account for spatial non-uniformity: run SLIP at one time (18 ns): E. A. Williams, later talk
- Provides 3D spatial beam intensity multiplier. Use this mask at all times
- Calculate SRS gain with spatially non-uniform transfer, and single intensities

The spatial non-uniformity of cross-beam transfer improves the correlation between SRS and gain
SRS gain with spatially non-uniform beam transfer tracks reflectivity better than with uniform transfer.

**Uniform Transfer**

- Gain increases due to long-wavelength “blip”

**Non-uniform Transfer**

- Gain increases due to long-wavelength “blip”

Diagram showing comparison between uniform and non-uniform transfer.
Threshold for electron trapping nonlinearity given by “bounce number” $N_B$

- **Electron trapping nonlinearities:**
  - Effective only if electrons resonant w/ Langmuir wave complete $\sim 1$ bounce orbit before being detrapped.

**Important detrapping processes:**
1. Speckle sideloss (geometric effect): $N_{B,sl}$
2. Collisions: electron-electron and electron-ion treated together: $N_{B,coll}$
   (SSD way too slow to matter)

\[
\text{Bounce number: } \quad N_B \equiv \frac{\tau_{de}}{\tau_B} = \frac{\text{detrapping time}}{\text{bounce period}} \sim \delta n^{1/2}
\]

\[
sideloss: \quad N_{B,sl} = \left[ \frac{\delta n}{\delta n_{sl}} \right]^{1/2} \quad \delta n_{sl} = 2.67 \left[ \frac{8}{F} \frac{\lambda_{De}}{\lambda_0} \right]^2
\]

\[
collisions: \quad N_{B,coll} = \left[ \frac{\delta n}{\delta n_{coll}} \right]^{3/2}
\]

Joint bounce number: $\quad N_B^{-1} = N_{B,sl}^{-1} + N_{B,coll}^{-1} \quad$ Independent detrapping rates add.
Trapping assessment of pF3D run suggests trapping occurs in parts of the 30 degree beam

pF3D:
- parallel, paraxial envelope code
- linear plasma response used

N110214 profiles, time = 18 ns:
- Trapping can change the local gain
- pF3D SRS reflectivity ~ 20%

Risk of trapping or Langmuir Decay Instability

\[ N_B \sim [\delta n_{LW}]^{1/2} \]
(sideloss and collisions)

\[ k_{LW} \lambda_{De} = 0.4 \]

DJS: AA SRS 2011; p. 11
Conclusions

- “High Flux Model” rad-hydro with spatially uniform cross-beam energy transfer:
  - SRS gain spectrum agrees well with measurements
  - Especially when multi-quad laser intensity used
  - Except for long-wavelength gains late in time – not seen in experiments

- Spatially uniform transfer: reflectivity and gain correlate until late in peak power
  - Late in time, reflectivity drops but gain does not

- Spatially non-uniform transfer: the correlation of reflectivity and gain improves

- Electron trapping: pF3D simulation shows regions in the beam where Langmuir wave amplitudes above threshold
  - May play a role in some of the SRS seen

A cross-beam transfer model, including spatial non-uniformity and plasma profile modification, is being added to Hydra
Backup slides after here
Observed SRS is consistent with the colder component of the hot electron spectrum

\[ \frac{dN}{dE} \sim \frac{E_1}{T_1^2} \exp\left[-\frac{E}{T_1}\right] + \frac{E_2}{T_2^2} \exp\left[-\frac{E}{T_2}\right] \]

“SRS component”: 
\[ E_1 = 70 \text{ kJ}, \quad T_1 = 18 \text{ keV} \]
\[ 0.5 m_e v_{\text{ph,LW}}^2 = 18 \text{ keV for } \lambda_{\text{SRS}} = 570 \text{ nm} \]
“conventional” backward SRS, measured in FABS/NBI

“Superhot component”: 
\[ E_1 = 0.8 \text{ kJ}, \quad T_1 = 124 \text{ keV} \]
independent LPI process, such as:
two-plasmon decay, backward SRS at \( n_{\text{crit}}/4 \), forward SRS, ...

x-ray spectra N110214, N110208 fit, N110211 fit

keV/keV.sr
1.0E+16
1.0E+15
1.0E+14
1.0E+13
1.0E+12
1.0E+11

keV
0 100 200 300 400

SRS component
Superhot (most preheat)

> 170 keV: source of capsule preheat

DJS: AA SRS 2011; p. 14
Significant gain can occur at longer wavelengths than measured on FABS

- Long-wavelength SRS washed out in ray-averaging, since each ray has a narrow peak (weak damping) at a different wavelength.

- Long-wavelength SRS may not occur: shorter-wavelength SRS occurs at lower density, nearer the LEH, and may deplete the pump.

- If it does occur, it will be more refracted than shorter-wavelength light [c.f. J. Moody’s talk] and may miss the FABS detectors.

- Also, it will be more absorbed in the target by inverse bremsstrahlung.

\[
\text{time} = 18 \text{ ns} - \text{mid peak power}
\]

- **FABS intensity [a. u.]**
- **multi-quad ray-avg. gain**
- **multi-quad log [ ray-avg. exp (G) ]**
Spatially varying beam transfer gives a wider distribution of ray gains

FOPAG = fraction of ray power above a gain.

For each ray: find the max gain within $\lambda = +/- 10$ nm of $\langle \lambda_{\text{max}} \rangle_{\text{avg}}$. 

single-quad gain, uniform xfer
multi-quad gain, uniform xfer
single-quad gain, varying xfer
Damping reduction and frequency shift in finite-radius Langmuir wave: theory by H. A. Rose

Damping Reduction:
more rapid in 2D than 3D

Frequency Downshift:
rapidly increases with $k\lambda_D$

![Graphs showing damping reduction and frequency downshift](image-url)
Fraction of coupling above a bounce number: allows quantification of trapping

\[ \frac{dE_{scat}}{dt}_{coup} \propto E_{las} \delta n_{epw} \]

63.9 ps [black], 65.5 ps [red], sideloss + collisions [solid], sideloss [dash]