Role of Electron Trapping in SRS on NIF Ignition Targets

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Summary

• Electron trapping nonlinearity can either enhance (damping reduction or “kinetic inflation”) or saturate (e.g., frequency shift) SRS.

• Simple assessment of whether trapping is likely provided by “bounce number.”
  – Number of bounce orbits completed before detrapping by collisions or geometric loss.
  – Damping reduction and frequency shift develop smoothly as bounce number increases; no hard threshold.

• Bounce-number assessments of NIF ignition designs show:
  – Trapping is unlikely on the outer beams, where SRS is weak.
  – Trapping may affect SRS on the inner beams, and more so on Be than CH ablators.
Likelihood of electron trapping nonlinearity quantified by “bounce number” $N_B$

- **Electron trapping nonlinearities** (e.g., inflation, frequency shift, Langmuir-wave self-focusing) are effective only if the electrons resonant w/ plasma wave complete $\sim 1$ bounce orbit before being detrapped.

![Diagram of electron trapping process](image)

**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)

Bounce number:
$$N_B \equiv \frac{\tau_{de}}{\tau_B} = \frac{\text{detrapping time}}{\text{bounce period}}$$

Bounce period:
$$\tau_B \equiv \frac{2\pi}{\omega_{pe}} \sqrt{\frac{n_e}{\delta n}}$$

Joint bounce number:
$$N_B^{-1} = N_{B,sl}^{-1} + N_{B,coll}^{-1} \quad \text{Independent detrapping processes.}$$

$i^{th}$ process:
$$N_{B,i} \equiv \frac{\tau_{de,i}}{\tau_B} = \left[ \frac{\delta n}{\delta n_{\text{thresh},i}} \right]^{p_i}$$

**Threshold:**
$$\delta n = \delta n_{\text{thresh},i} \rightarrow N_{B,i} = 1$$

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Rose calculation of nonlinear transit-time damping in finite speckle give $N_B \approx 1$ for significant damping reduction.

Transit time damping decreases faster in 2D than 3D

$$\frac{\nu_L(\phi)}{\nu_L(\phi = 0)} \approx G \left( \frac{\omega_b}{\nu_{\text{side loss}}} \right)$$

$$v_{\text{side loss}} \sim v_e / (\text{Langmuir wave scale length})$$

Transit time damping depends weakly on $k\lambda_D$

*With reduced damping a given high-frequency beat ponderomotive force drives a larger Langmuir wave, so $N_B$ from the linear $\delta n$ is an under-estimate.

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Sideloss threshold: lower in 2D than 3D

\[ N_{B,sl} = \frac{\tau_{sl}}{\tau_B} = K_{sl} \frac{L_{\perp}}{v_{Te} \tau_B} = \left[ \frac{\delta n}{\delta n_{sl}} \right]^{1/2} \]

\( K_{sl} = (0.98, 0.48) \) in (2D, 3D)
(thermal Maxwellian leaving cylinder)

Speckle sideloss:

\[ L_{\perp} \approx F\lambda_0 \]

\[ \frac{\delta n_{sl}}{n_e} \equiv 1.33 \cdot 10^{-4} \left[ \frac{8}{F} \right]^2 \frac{n_c}{n_e} T_{e,kV} \quad [3D] \]

Endloss also occurs, usually much slower:

\[ \tau_{el} \sim \frac{L_{\parallel}}{v_{phase}} \quad L_{\parallel} \sim 5F^2 \lambda_0 \]

\[ \frac{\tau_{sl}}{\tau_{el}} \sim \frac{1}{5F} \frac{v_{phase}}{v_{Te}} \ll 1 \]

Collisional thresholds: e-e and e-i treated together

\[ \frac{\partial f}{\partial t} = \nu_{ei} \frac{\partial f}{\partial \mu} (1 - \mu^2) \frac{\partial f}{\partial \mu} + 2\nu_{eet} \frac{v_i^2}{v^2} \frac{\partial f}{\partial v} \left( f + \frac{v_i^2}{v} \frac{\partial f}{\partial v} \right) \]

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

\[ \frac{\delta n_{coll}}{n_e} \equiv \left[ 2\pi \ln 2 \frac{\nu_{ei} (v = v_T)}{\omega_p} \left( \frac{k\lambda_D}{3} \right)^2 \right]^{2/3} \]

For \( v_p >> v_{Te} \):

\[ \tau_{coll} \approx \frac{28.4}{3 + Z_{eff}} n_e \lambda_{De}^3 \left( \frac{\omega}{\omega_{pe}} \right)^3 \frac{\delta n}{n_e} + O\left( \frac{v_p}{v_{Te}} \right)^2 \]

Depends on wave amplitude \( \delta n \), unlike sideloss

Trapping threshold for sideloss usually dominates collision threshold, but collisions can matter for high-Z, cold, low-density plasmas

\[
dN = \frac{dn}{n_e}
\]
Overview of trapping risk for NIF designs

- **outer beam, off peak**: Pierre Michel looked w/ SLIP closer to LEH than max gain (higher $T_e$, lower $n_e$, higher $k\lambda_{De}$); even less risk than on-resonance.
- **outer beam, peak**: SRS is linearly weak, stays below trapping threshold; nonlinearity not a concern.
- **inner beam, off peak**: assessed with ray-based DEPLETE code.
- **inner beam, peak**: Trapping may occur here, but does it inflate or saturate?

* **"Peak" SRS**: at scattered wavelength of max gain; we generally envelope around this in pf3d. Assessed by post-processing the Langmuir waves driven in pf3d.

* **"Off peak" SRS**: at wavelengths with lower linear gain; less SRS expected, but a pf3d run won’t include it unless we envelope around an off-peak wavelength.

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Outer beam peak SRS: pf3d run of 50 deg. beam, $T_{\text{rad}} = 285$ eV, Be ablator, at 12 ns (peak power)

pf3d SRS reflectivity $\sim 10^{-6}$

Off-peak outer beam:
Examined by Pierre Michel w/ SLIP, trapping even less of a concern.
Outer beam peak SRS: bounce number $<< 0.5$ almost everywhere: trapping is not a concern (same results for CH design)
Off peak inner beam SRS: bounce number assessment shows little risk for kinetic inflation

Off-Peak Bounce Number Analysis from DEPLETE

“Peak” Bounce Number from pF3D simulations

CH capsule (300 eV)

Be capsule (285 eV)

Inner beam peak SRS: post-process pF3D run of CH ablator, 300 eV radiation temperature, LEH liner

Escaping SRS Light

Conditions on longitudinal (yz) plane, 82 ps

Pump laser intensity
SRS light intensity
Langmuir wave $\delta n/n_e$
CH ablator case: conditions at run end (82.4 ps)

Bounce number, longitudinal plane

transverse-averaged bounce number (laser weighted)

transverse-averaged laser power (a.u.)

Fraction of scattered coupling ($E_{\text{las}} \cdot \delta n^*$) above a bounce number, $z = 0.47$ cm
Comparison of CH and Be ablators: more SRS, and more trapping risk, in Be

Fraction of scattered coupling (Elas•dn*) above a bounce number, over xy plane

Bounce number at z = 63 cm
Summary and Future Work

• “Bounce number” provides a simple assessment of whether electron trapping nonlinearity can overcome detrapping processes (sideloss, collisions).
  – Sideloss is usually the dominant detrapping process.

• SRS on NIF outer beams seems below trapping threshold.

• SRS on NIF inner beams are more worrisome; designs with CH ablators less so than Be.

• A reduced model is needed to quantitatively study trapping effects: does it enhance SRS (inflation) or saturate it?

• Work is underway to implement such a model in pF3D, and benchmark it against kinetic simulations (R. Berger, H. Rose, D. Strozzi).
1D Vlasov simulations with Sapristi\(^1\) of driven EPW’s in LEH conditions: departures from linear theory, even though \(N_B >> 1\)

Homogenous, periodic plasma: 
\(n_e/n_{\text{crit}} = 0.07\) \(T_e = 5\) keV; 
\(\nu_{\text{Krook}} = 4.3E-4\omega_{pe}\) (sideloss for \(L_{\text{perp}} = 100\) um)

Krook relaxation:  
\[
\partial_t f |_{\text{Krook}} = \nu_K \cdot (n\hat{f}_0 - f)
\]

Bounce number in linear field >> 1 
\[
N_B = \frac{\omega_B}{2\pi \nu_K} = 14.3
\]

Distribution for \(k\lambda_{De} = 0.54\), \(t\omega_{pe} = 750\): phase-space vortices; x-avged \(f\) flattened

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\(^1\) S. Brunner, E. J. Valeo, PRL 93, 145003 (2004).
Reduced model by H. Rose, for Langmuir waves of finite transverse size

Damping reduction: \[
\frac{v}{v_{\text{Landau}}} = f + 0.4(1-f) \frac{v_{\text{esc}}}{v_{\text{Landau}}} \quad f = \exp\left[-\ln 2 \cdot \left(\frac{2\pi}{3(D-1)}\right)^2 N_B^2\right] \quad D = \text{dimensionality} = 2, 3
\]

Frequency shift: \[
\frac{\delta \omega}{\omega_B} = -0.88 \left(\frac{v_p}{v_{Te}}\right)^3 f_{mwx}''(v_p/v_{Te}) \cdot (1-f) \quad \frac{v_{\text{esc}}}{v_{\text{Landau}}} \sim \frac{v_{Te}}{L_\perp} \quad \text{Depends on } k\lambda_D, \text{2D/3D}
\]

Benchmarked by transit-time damping and PIC calculations.
DEPLETE\textsuperscript{1} performs ray-based, steady-state backscatter calculations

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

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

\text{inv. brems. damping} \quad \text{brems. source} \quad \text{Thomson scattering} \quad \text{SBS/SRS coupling}

\textbf{The code DEPLETE does:}
\begin{itemize}
  \item use 1-D plasma conditions from 3-D ray-trace
  \item handle a spectrum of scattered frequencies
  \item use a strong damping limit plasma-wave
  \item deplete the laser pump
  \item use Thomson scatter/bremsstrahlung noise sources
  \item inverse-bremsstrahlung light wave damping
  \item use linear kinetic coupling coefficients
  \item include collisional damping of Langmuir waves
  \item model whole-beam focusing
\end{itemize}

\textbf{The code DEPLETE does not:}
\begin{itemize}
  \item include temporal effects
  \item include laser speckle effects
  \item include multi-D effects
\end{itemize}


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