Assessing risk of plasma-wave trapping nonlinearities in stimulated Raman scattering

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Electron trapping nonlinearities in SRS have attracted significant attention in recent years.

**Electron trapping nonlinearities:**
- inflation\(^1\-^2\).
- frequency shift\(^3\-^5\).
- modulational instability\(^6\).
- Langmuir-wave self-focusing\(^7\-^8\).

Trapping is effective only if electrons resonant w/ plasma wave complete ~ one bounce orbit before being detrapped.

**Detrapping processes:**
- Speckle sideloss, endloss (geometric effects).
- Collisions: both electron-electron and electron-ion treated together.
- SSD (temporal decorrelation).

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Bounce number = number of bounce orbits resonant electrons complete before being detrapped

<table>
<thead>
<tr>
<th>Description</th>
<th>Equation</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Bounce number(^1):</td>
<td>( N_B \equiv \frac{\tau_{de}}{\tau_B} )</td>
<td>bounce orbits a resonant e-completes before it’s detrapped.</td>
</tr>
<tr>
<td>Bounce period:</td>
<td>( \tau_B \equiv \frac{2\pi}{\omega_{pe}} \delta N^{-1/2} )</td>
<td>( \delta N \equiv \delta n / n_e )</td>
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<tr>
<td>Total detrapping time:</td>
<td>( \tau_{de} \equiv 1 / \nu_{de} )</td>
<td>Sum rates for each detrapping process: probability e- detrapped in time ( dt = ) sum of prob. detrapped by each process</td>
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<tr>
<td></td>
<td>( \nu_{de} \equiv \sum_i \nu_i )</td>
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<tr>
<td>Bounce number for one detrapping process:</td>
<td>( N_{Bi} \equiv \frac{1}{\tau_B \nu_i} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( N_B^{-1} = \sum_i N_{Bi}^{-1} )</td>
<td>bounce numbers add in reciprocal; dominated by fastest detrapping process</td>
</tr>
</tbody>
</table>

\(^1\)D. J. Strozzi, E. A. Williams, A. B. Langdon, and A. Bers; Phys. Plasmas 14, 013104 (2007).
Detrapping due to speckle sideloss, and perhaps collisions, can be approximately modeled in 1D by a Krook operator

**Krook operator:**

\[
\frac{\partial_t f}{\nu_K(\delta N)}\left[n\hat{f}_0 - f\right] = \hat{f}_0 = \text{normalized Maxwellian}
\]

- e-folding decay time for a feature in f is \(\tau_e = 1/\nu_K\).
- For collisional loss, effective \(\nu_K\) depends on wave amplitude \(\delta N\).

\[\tau_e = \text{detrapping time} \quad \Rightarrow \quad N_B = \frac{\tau_e(\delta N)}{\tau_B}\]
Trapping threshold for “NIF inner SRS” parameters from 1D Vlasov simulations with ELVIS code

\[ \partial_t f = \nu_K \cdot \left[ n \hat{f}_0 - f \right] \]

Krook operator

- “NIF inner SRS” parameters: \( n_e/n_c = 0.115 \), \( T_e = 2.1 \) keV; \( k_{epw} \lambda_D = 0.275 \).
- Backscattered seed: \( I_1/I_0 = 10^{-6} \); bandwidth 0.04\( \omega_p \).
- Focusing factor: FWHM = 181\( \lambda_0 \) ( = 5\( F^2 \lambda_0 \) for \( F = 6 \)).

No Krook: Trapping threshold: speckle endloss

With Krook; \( I_0 = 10^{15} \) W/cm\(^2\)

Absolute instability threshold: \( I_{ab} = 2 \cdot 10^{15} \) W/cm\(^2\)
Time-dependent reflectivities and bounce numbers for “NIF inner SRS” parameters: \( N_B = 1 \) is a decent estimate for inflation

\[ \nu_K = 2 \cdot 10^{-3} \]
\[ \nu_K = 4 \cdot 10^{-3} \]
\[ \nu_K = 6 \cdot 10^{-3} \]

\[ \log_{10}(N_B) \]
\[ N_B \text{ (linear)} \]
\[ N_B \text{ (linear)} \]
Detrapping due to speckle sideloss

- Speckle diameter $L \approx F\lambda_0$; lifetime of resonant e-w/ transverse speed $v_e$:
  \[ \tau_{sl} \approx L/v_e \]

- Kinetic calculations by Ed Williams [prior talk] shows the time for $1/e$ of the particles with a given longitudinal velocity to leave a cylinder of diameter $L$ is:
  
  2D: \[ \tau_{e2} = 0.88 \frac{L}{v_e} \]
  3D: \[ \tau_{e3} = 0.48 \frac{L}{v_e} \]

- Rose 3D calculations show, 50% reduction in transit-time damping for $\tau_{e3,tt} \approx L/v_e$.

- NIF example: $F=8$, $\lambda_0=351$ nm, $\tau_{e3} = 0.10$ ps / $T_{e,kV}^{1/2}$

- Using $\tau_{e3}$ and $L = F\lambda_0$:

  \[
  N_B = \frac{\tau_{e3}}{\tau_B} = \left[ \frac{\delta N}{\delta N_{sl}} \right]^{1/2} \quad \delta N_{sl} \equiv 1.33 \cdot 10^{-4} \left[ \frac{8}{F} \right]^2 \frac{n_c}{n_e} T_{e,kV}
  \]
Calculation of nonlinear transit-time damping in finite speckle by Rose give $N_B \approx 1$ for significant damping reduction.

Transit time damping decreases faster in 2D than 3D.

Transit time damping depends weakly on $k \lambda_D$.

\[
\frac{\nu_L(\phi)}{\nu_L(\phi = 0)} \approx G \left( \frac{\omega_b}{v_{\text{side loss}}} \right)
\]

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

D. J. Strozzi, Anomalous 2008, p. 8
Electron-electron and electron-ion collisions provide a threshold, which we compute in a unified way

- Collision operator:
  \[ \partial_t f = v_{ei} \partial_\mu \left[ (1 - \mu^2) \partial_\mu f \right] + 2v_{ee} \frac{v_T}{v^2} \partial_v \left[ f + \frac{v_T}{v} \partial_v f \right] \]

  \[ v_{ee} = \frac{1}{8\pi n_e \lambda_{De}^3} \left[ \frac{v_T}{v} \right]^3 \ln \Lambda_{ee} \quad v_{ei} = v_{ee} \hat{Z} \quad \hat{Z} \equiv 1 + \sum_{i=\text{ions}} Z_i^2 \frac{n_i}{n_e} \frac{\ln \Lambda_{ei}}{\ln \Lambda_{ee}} \]

- Ed Williams analysis [prior talk]: time for half e- to escape:
  \[ v_{ei} (v = v_T) t_{1/2} = (k\lambda_D)^{-2} G \left[ v_p / v_T, \hat{Z} \right] \cdot \delta N \]

- Detrapping rate (= e-fold time):
  \[ \tau_{coll} = \frac{t_{1/2}}{\ln 2} \]

- Bounce number:
  \[ N_{B,coll} = \frac{\tau_{coll}}{\tau_B} = \left[ \frac{\delta N}{\delta N_{coll}} \right]^{3/2} \quad \delta N_{coll} \equiv 2\pi \ln 2 \frac{v_{ei} (v = v_T) (k\lambda_D)^2}{\omega_p G} \]

D. J. Strozzi, Anomalous 2008 p. 9
Rose collisions analysis: e-e collisions weakly modify the transit-time (Landau) damping rate

\[
\frac{d(KE)}{dt} \propto \frac{v_{\text{coll}} \times \phi^{3/2}}{v_{\text{Landau}} \phi^2}
\]

Transit time damping

\[
\propto \frac{v_{\text{coll}}}{\sqrt{\phi}} \propto \frac{v_{\text{coll}}}{\omega_p} \frac{F}{\lambda_D}
\]

Distribution for BGK mode, used to calculate heating rate

When e-e heating rate \( \sim \) transit-time damping rate, e-e heating matters when trapping has reduced t-t damping rate by 50% (rough inflation criterion).
SSD imposes a very low threshold due to temporal decorrelation of pump field, will not affect trapping

\[ N_{B,ssd} \equiv \frac{\tau_{ssd}}{\tau_B} = \left[ \frac{\delta N}{\delta N_{ssd}} \right]^{1/2} \]

\[ \delta N_{ssd} \equiv \frac{n_c}{n_e} \left[ \frac{\Delta \lambda_{\text{red}}}{\lambda_{\text{red}}} \right]^2 \]

\[ \tau_{ssd} \equiv \tau_{\text{blue}} \frac{\lambda_{\text{red}}}{\Delta \lambda_{\text{red}}} \]

Approximate intensity auto-correlation time, in blue (3\(\omega\)).

= 6.2 ps for \(\Delta \lambda_{\text{red}} = 2 \) Ang.

**SSD threshold for \(\Delta \lambda_{\text{red}} = 2 \) Ang.**

Much lower than thresholds due to sideloss or collisions.
Trapping threshold for sideloss usually dominant, but collisions can be larger in high-Z material.

\[ \frac{dN_{\text{coll}, \text{CH}}}{dN_{\text{sl}}} \]

\[ \frac{dN_{\text{coll}, \text{AuB}}}{dN_{\text{sl}}} \]
NIF design “test24”: Rev 3, $T_{\text{rad}} = 300$ eV, CH ablator, at 15.5 ns (peak power)

pF3D run: srs matching: $n_e = 0.105n_c$, $T_e = 5.2$ keV
$\rightarrow k\lambda_D = 0.44$

Design by D. Callahan (LLNL)

D. J. Strozzi, Anomalous 2008 p. 13
“test24” (300 eV, CH ablator): collisions matter for threshold in high-Z material

$\delta N_{\text{joint}}$ (sideloss+collisions)

$\delta N_{\text{joint}} / \delta N_{\text{sideloss}}$: sideloss within 2x of joint threshold
pF3D backscatter simulation on 50° cone of “test24” design: full beam path length and 

\[ \log_{10}(\delta n/n_e) \] SRS Langmuir wave

\[ \log_{10}(\delta n/n_e) \] SRS Langmuir wave near wall

SRS light wave intensity (a.u.)

pF3D run “tg50t24_l01”
pF3D 50° cone run: bounce number well below threshold of \( \sim 1 \); trapping seems to not be a concern

But there may be brief times when intense speckles do inflate.
Summary and other talks

- **N$_B$ bounce number**: $\approx 1$ for trapping nonlinearity in SRS Langmuir waves.
  - Includes speckle sideloss and collisions.

- **Speckle sideloss**: typically the dominant detrapping mechanism, but collisions can matter in high-Z plasmas.

- **SSD**: too slow to affect trapping for Langmuir-wave amplitudes $\delta n/n_e > 10^{-6}$.

- **NIF**: Rev 3, $T_{rad} = 300$ eV, CH ablator, outer (50°) beam:
  - Trapping threshold: Langmuir wave $\delta n/n_e > 5\cdot10^{-3}$.
  - pF3D simulations give amplitudes generally far below this; very few points having bounce numbers above 0.5.

- **Inner beam**: under investigation; SRS generally more active than on outer beam.

Other related SRS presentations:
- Dodd: poster Tues. night
- Everything this session: Langdon, Yin, Williams, Vu
- Fahlen, Winjum posters