Role of Electron Trapping in SRS on NIF Ignition Targets

D. J. Strozzi[1], E. A. Williams[1], D. E. Hinkel[1], H. A. Rose[2]

[1]Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550, USA
[2]Los Alamos National Laboratory
Los Alamos, NM 87545, USA

Talk FO4
Anomalous Absroption Meeting
Bodega Bay, CA, USA
19 June 2009

This work performed under the auspices of the U.S. DoE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Supported by LDRD Project 08-ERD-017.
Release number LLNL-PRES-413928.

Summary

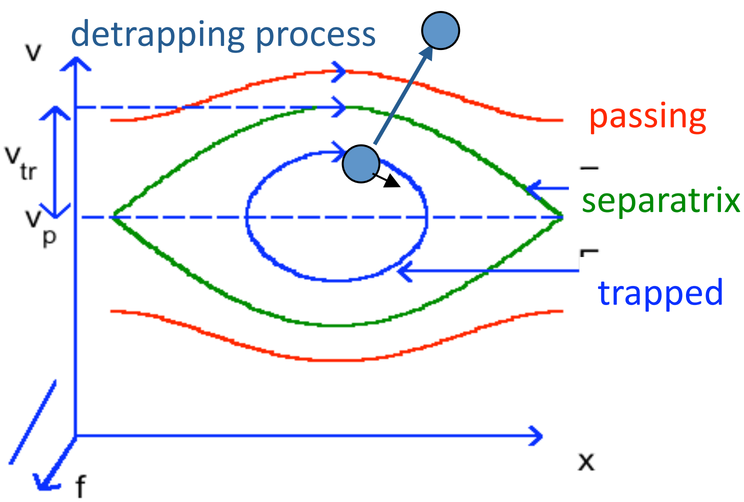
- Electron trapping nonlinearity can either enhance (damping reduction or "kinetic inflation") or saturate (e.g., frequency shift) SRS.

- 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 ~ 1 bounce orbit before being detrapped.



Imporant 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: $N_B \equiv \dfrac{\tau_{de}}{\tau_B} = \dfrac{\text{detrapping time}}{\text{bounce period}}$

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

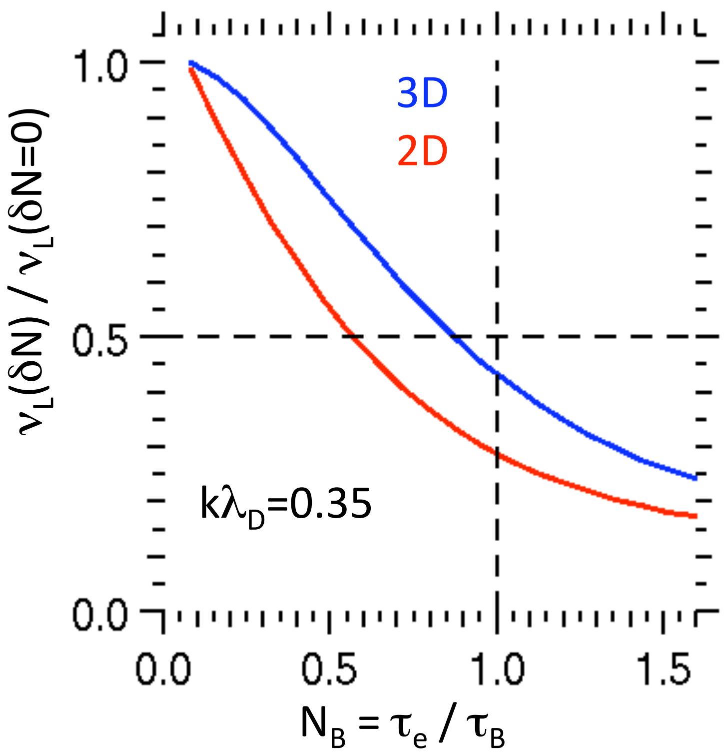
Joint bounce number: $N_B^{-1} = N_{B,sl}^{-1} + N_{B,coll}^{-1}$ Independent detrapping processes.

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

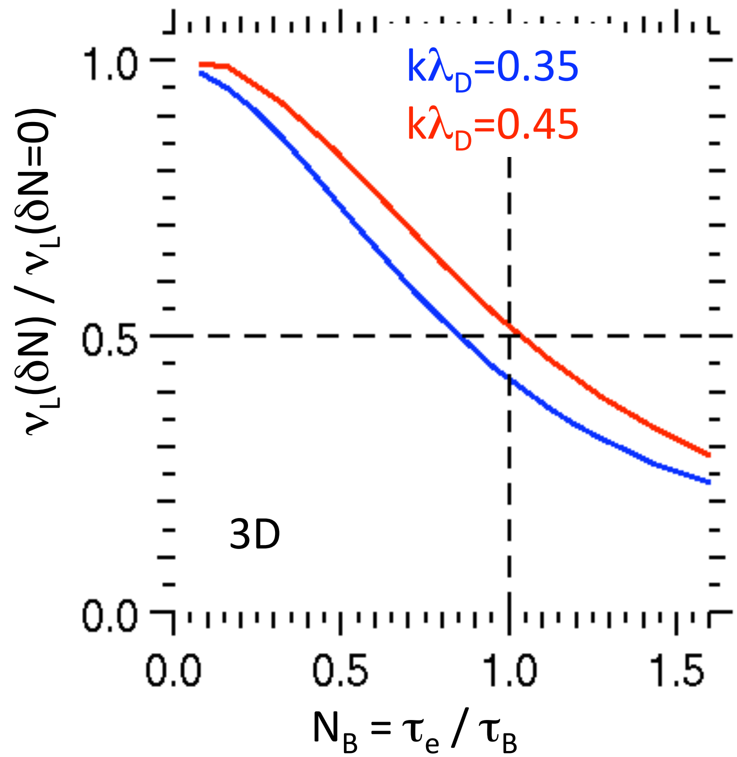
Threshold: $\delta n = \delta n_{\text{thresh,i}} \quad \rightarrow \quad N_{B,i} = 1$

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



Transit time damping depends weakly on $k\lambda_D$

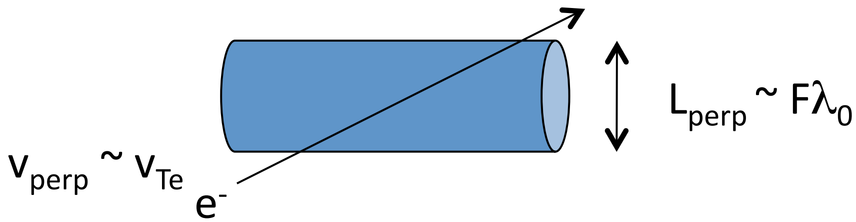


$$\frac{\nu_L(\phi)}{\nu_L(\phi=0)} \approx G\left(\frac{\omega_b}{\nu_{\text{side loss}}}\right)$$

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

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

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:

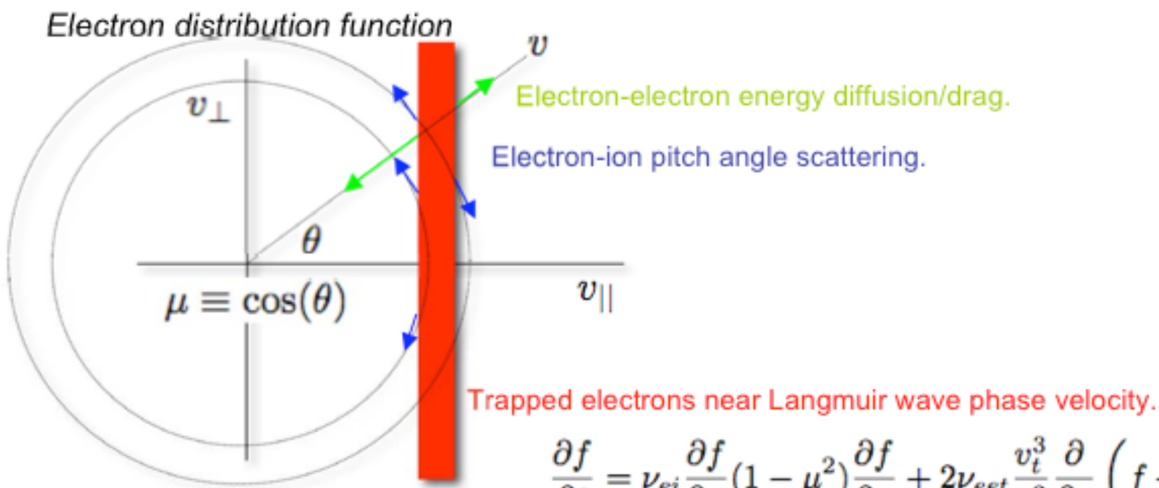
$$L_\perp \approx F\lambda_0 \qquad \frac{\delta n_{sl}}{n_e} \equiv 1.33\cdot 10^{-4}\left[\frac{8}{F}\right]^2 \frac{n_c}{n_e} T_{e,kV}$$ **[3D]**

Endloss also occurs,
usually much slower:

$$\tau_{el} \sim \frac{L_\parallel}{v_{\mathrm{phase}}} \qquad L_\parallel \sim 5F^2\lambda_0 \qquad \frac{\tau_{sl}}{\tau_{el}} \sim \frac{1}{5F}\frac{v_{\mathrm{phase}}}{v_{Te}} << 1$$

[1] E. A. Williams, D. J. Strozzi, et al., Anomalous Absorption Meeting, 2008.

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



$$\frac{\partial f}{\partial t} = \nu_{ei}\frac{\partial f}{\partial \mu}(1-\mu^2)\frac{\partial f}{\partial \mu} + 2\nu_{eet}\frac{v_t^3}{v^2}\frac{\partial}{\partial v}\left(f + \frac{v_t^2}{v}\frac{\partial f}{\partial v}\right)$$

$$N_{B,coll} = \frac{\tau_{coll}}{\tau_B} = \left[\frac{\delta n}{\delta n_{coll}}\right]^{3/2} \qquad \frac{\delta n_{coll}}{n_e} \equiv \left[2\pi \ln 2 \frac{\nu_{ei}(v = v_T)}{\omega_p}\frac{(k\lambda_D)^2}{G[v_{ph}/v_{Te}, Z_{eff}]}\right]^{2/3}$$

For $v_p \gg v_{Te}$:

$$\tau_{coll} \approx \frac{28.4}{3+Z_{eff}}\frac{n_e\lambda_{De}^{\ 3}}{\ln\Lambda}\frac{(\omega/\omega_{pe})^3}{(k\lambda_{De})^5}\frac{\delta n}{n_e} + O\left(\frac{v_p}{v_{Te}}\right)^2$$

3 (e-e energy diffusion/drag + pitch angle)

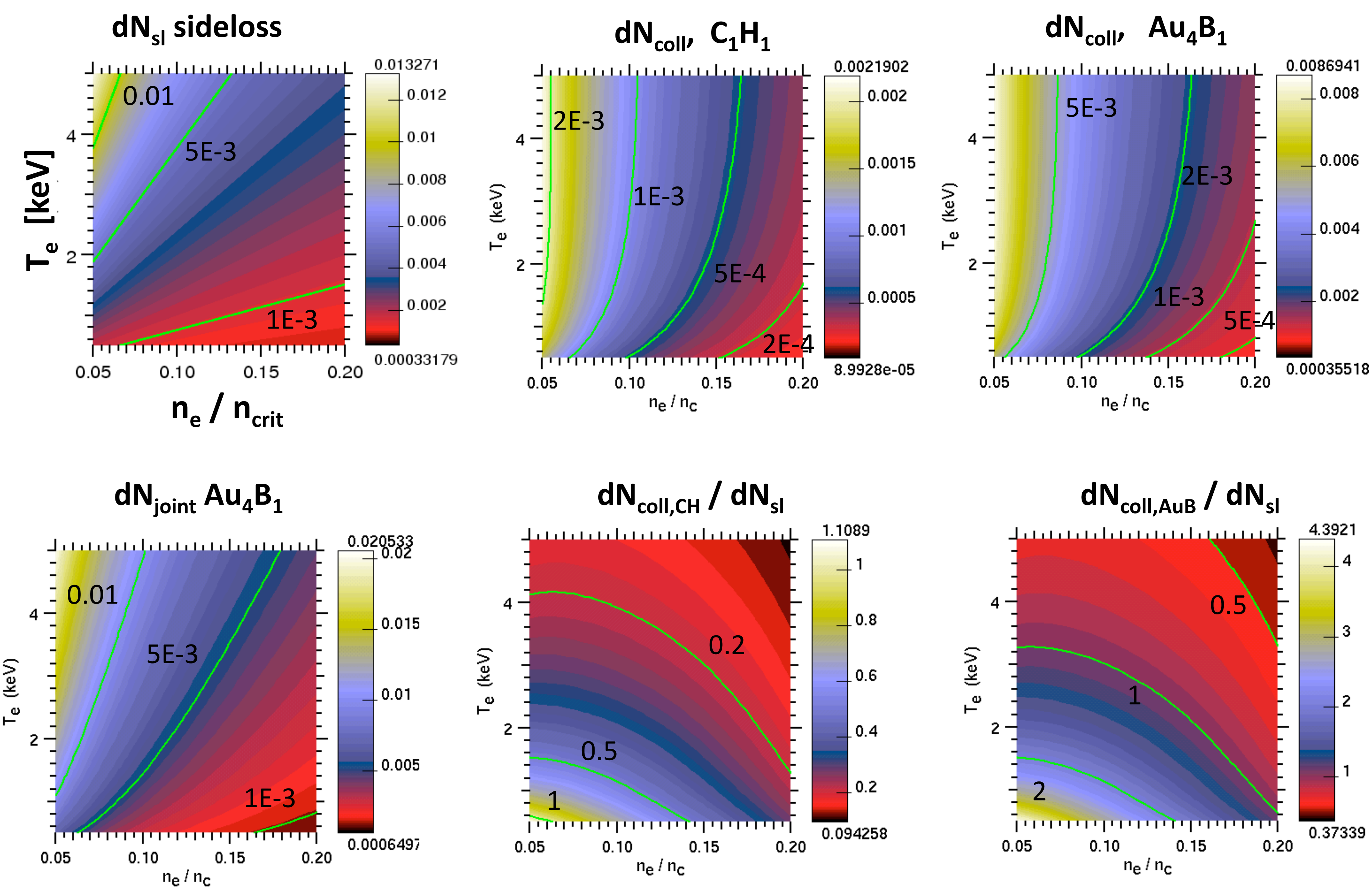
+ Z_{eff} (e-ion pitch angle)

Depends on wave amplitude δn, unlike sideloss

[1]E. A. Williams, D. J. Strozzi, et al., Anomalous Absorption Meeting, 2008.

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

$dN = dn/n_e$



Overview of trapping risk for NIF designs

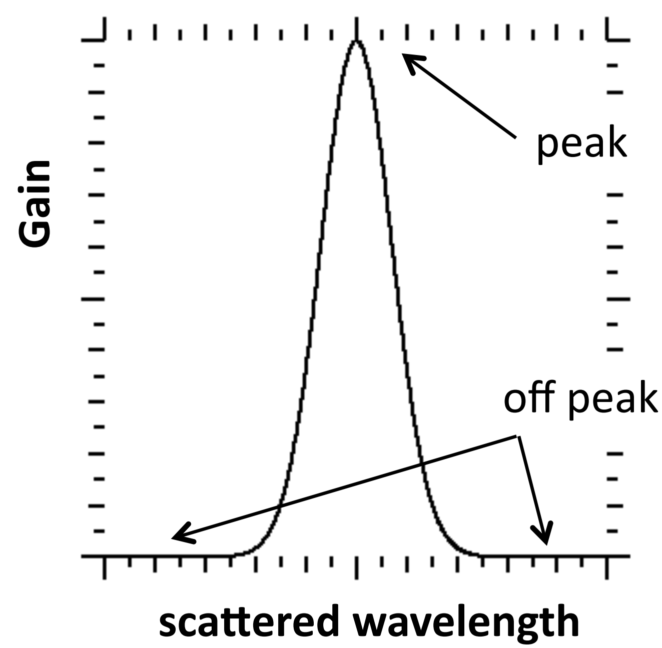
trapping more likely ↓

- 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?

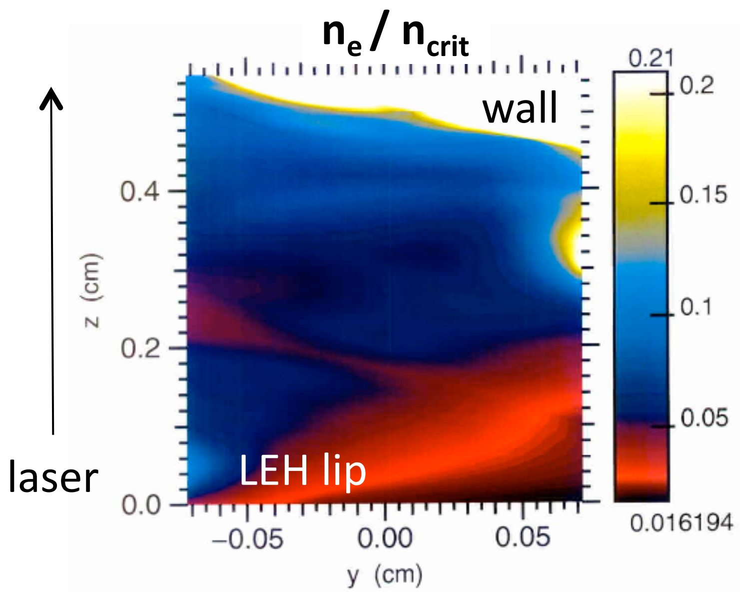
* **"Peak" SRS:** at scattered wavelength of max gain; we generally envelope around this in pf3d. Assessed by post-processing the Langmuir waves driven in pf3d.

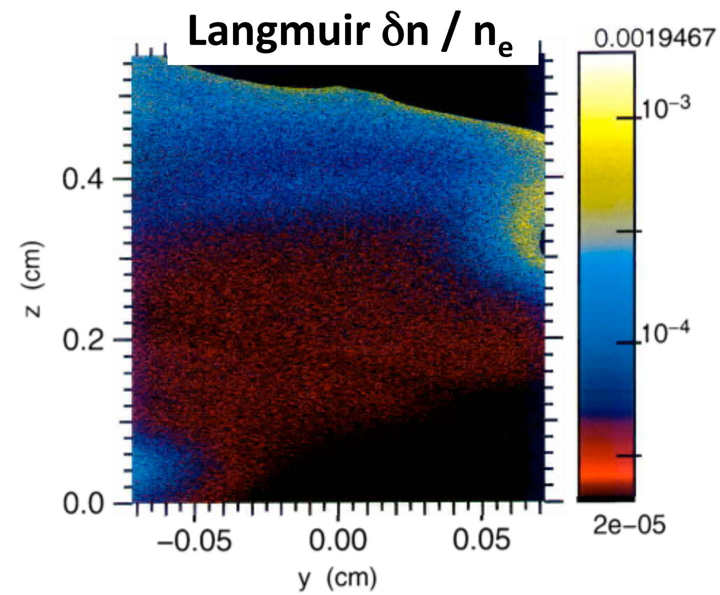
* **"Off peak" SRS:** at wavelengths with lower linear gain; less SRS expected, but a pf3d run won't include it unless we envelope around an off-peak wavelength.

Generic gain curve

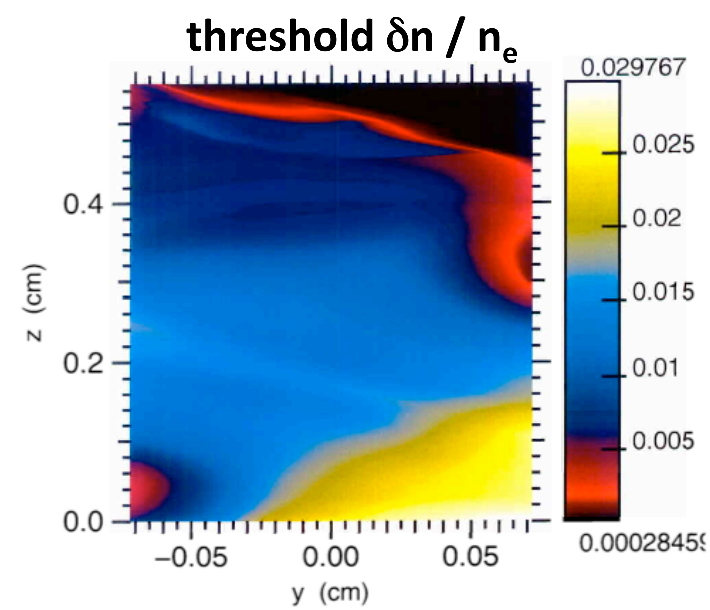


Outer beam peak SRS: pf3d run of 50 deg. beam, T_{rad} = 285 eV, Be ablator, at 12 ns (peak power)





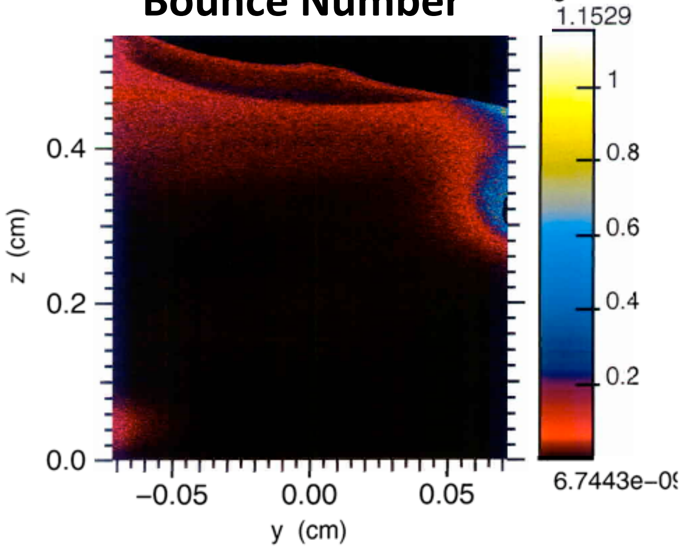
pf3d SRS reflectivity ~ 10^{-6}



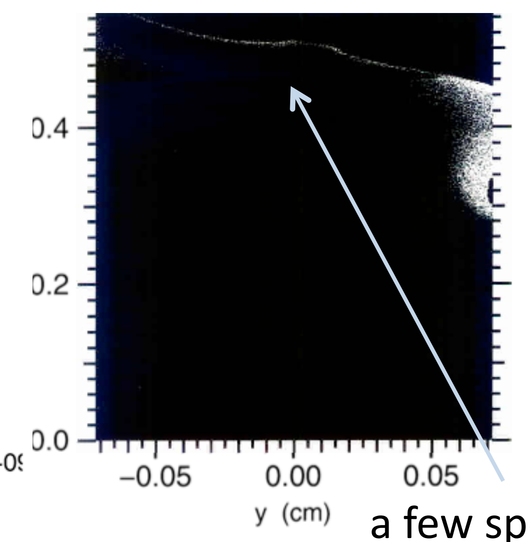
Off-peak outer beam: Examined by Pierre Michel w/ SLIP, trapping even less of a concern.

Outer beam peak SRS: bounce number << 0.5 almost everywhere: trapping is not a concern (same results for CH design)

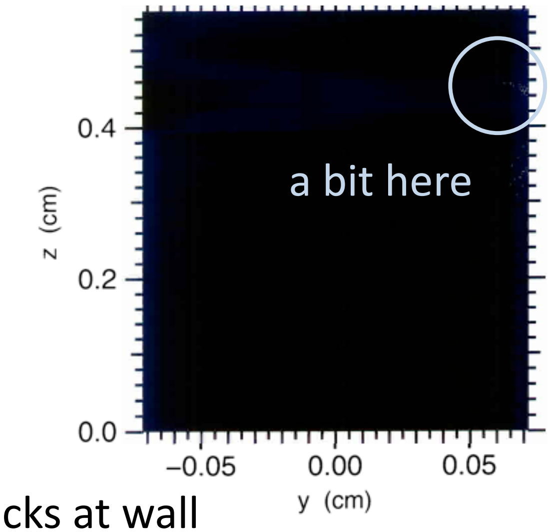
Bounce Number



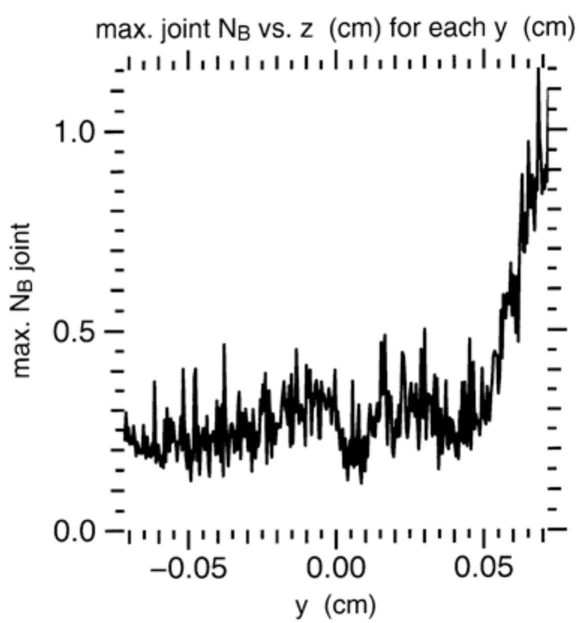
Bounce Number > 0.2

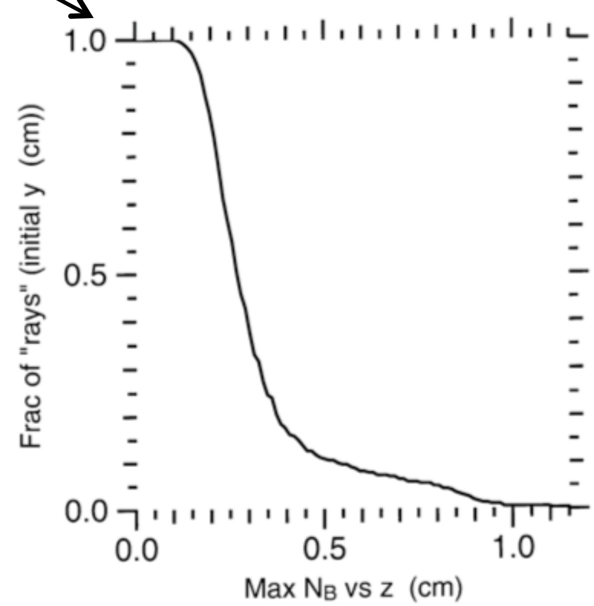


Bounce Number > 0.8



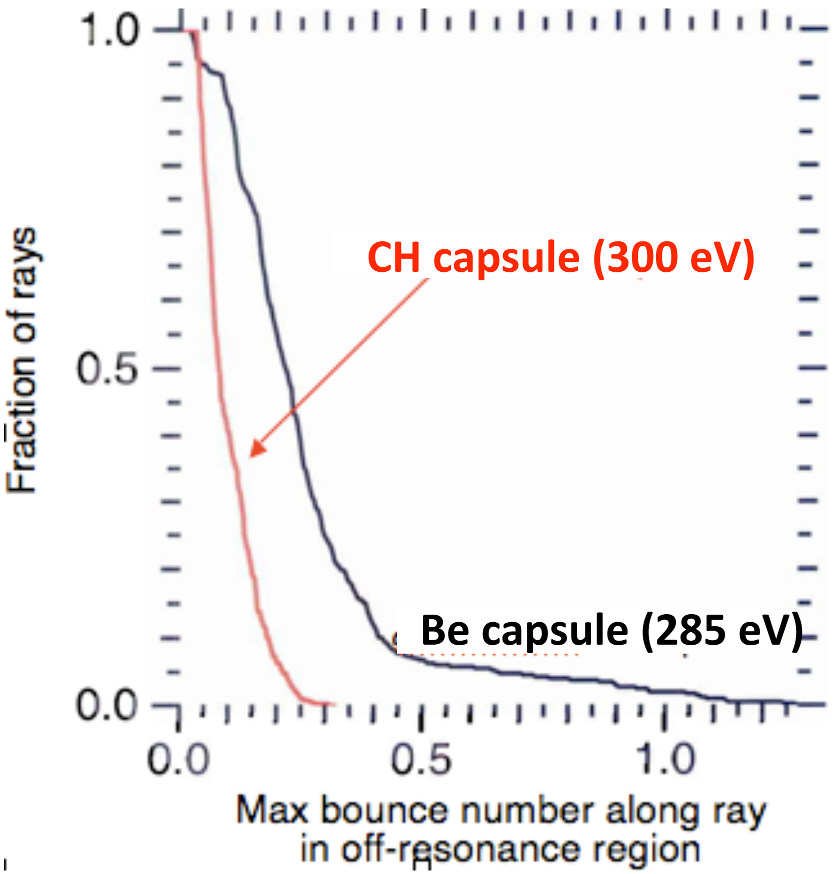
a few specks at wall



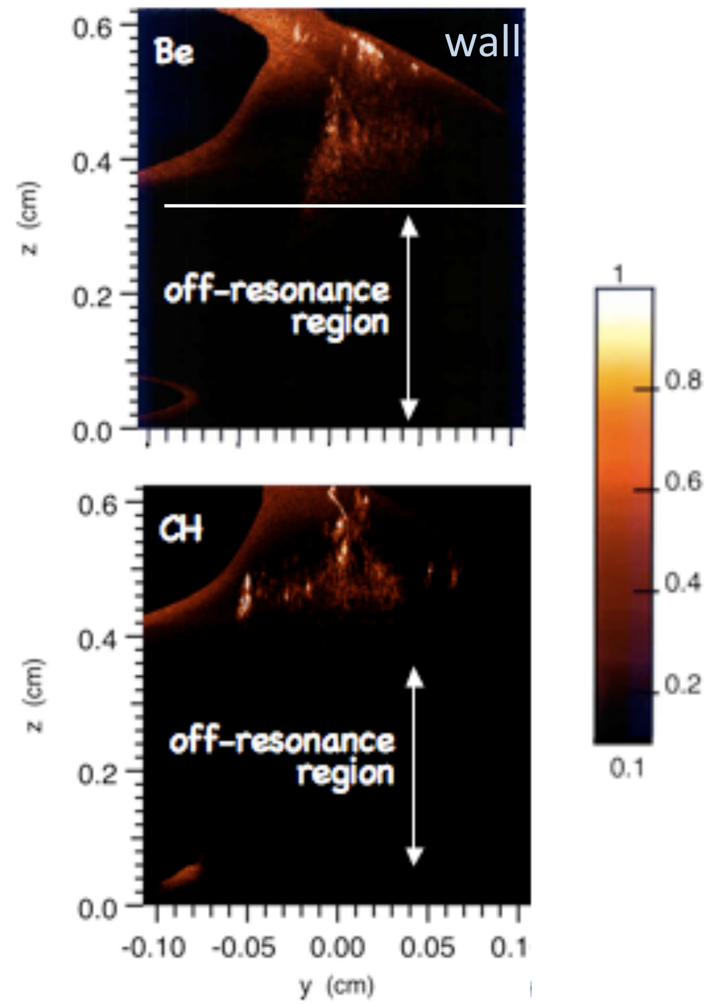


Off peak inner beam SRS: bounce number assessment shows little risk for kinetic inflation

Off-Peak Bounce Number Analysis from DEPLETE[1]



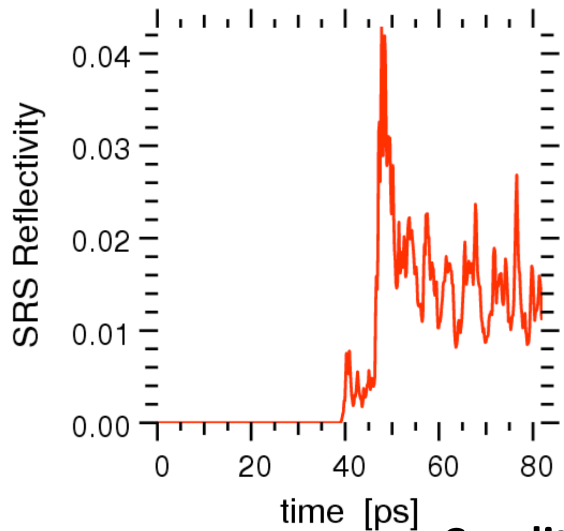
"Peak" Bounce Number from pF3D simulations



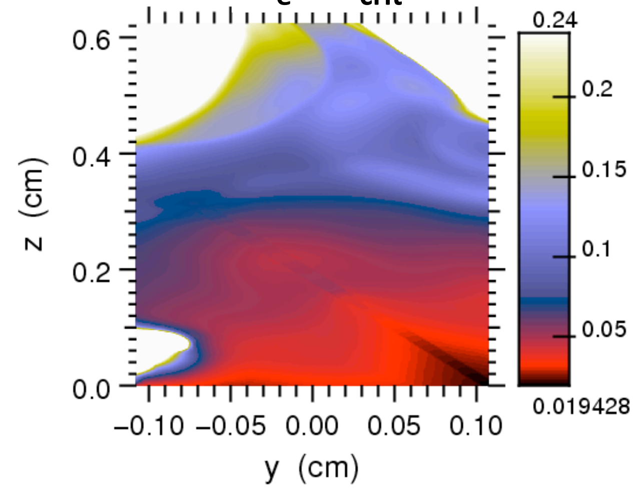
[1]D. J. Strozzi *et al.,* Phys. Plasmas 15, 102703 (2008)

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

Escaping SRS Light

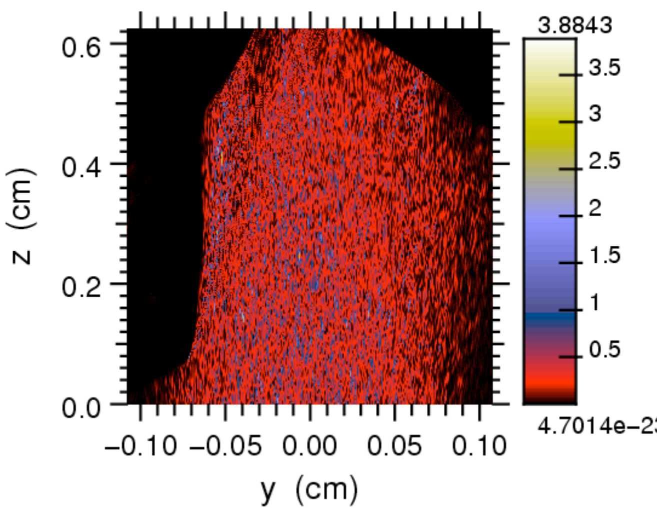


n_e / n_{crit}

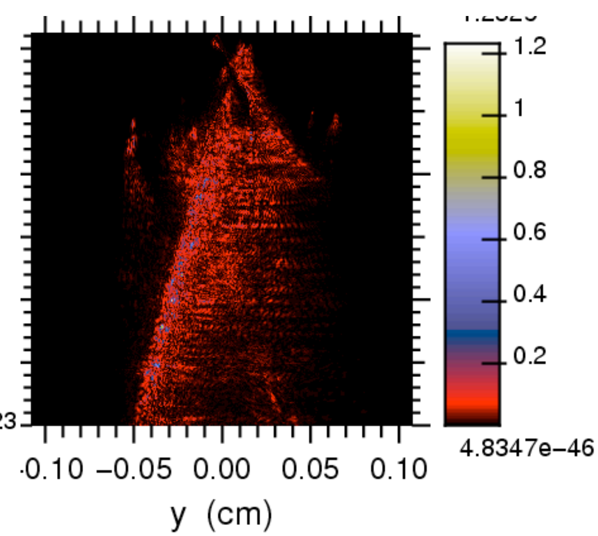


Conditions on longitudinal (yz) plane, 82 ps

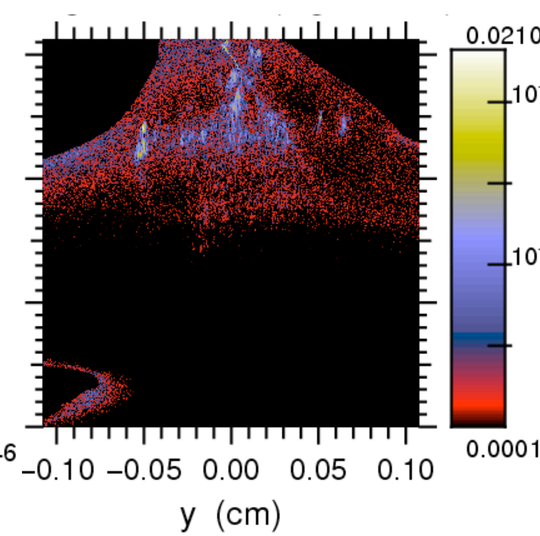
Pump laser intensity



SRS light intensity

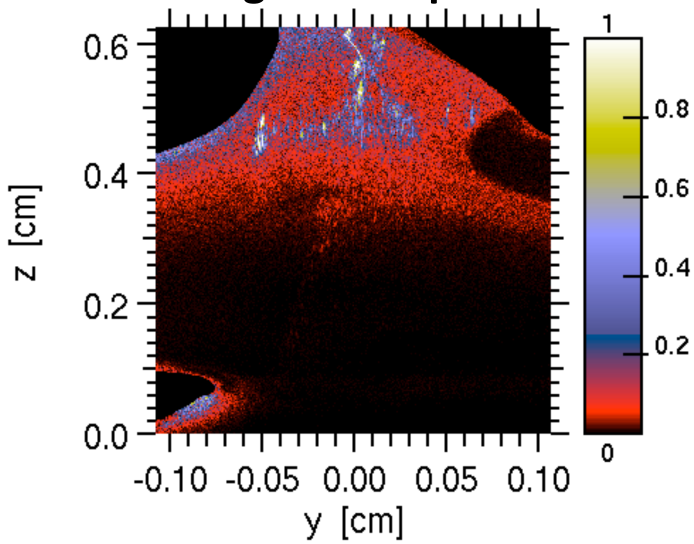


Langmuir wave $\delta n/n_e$

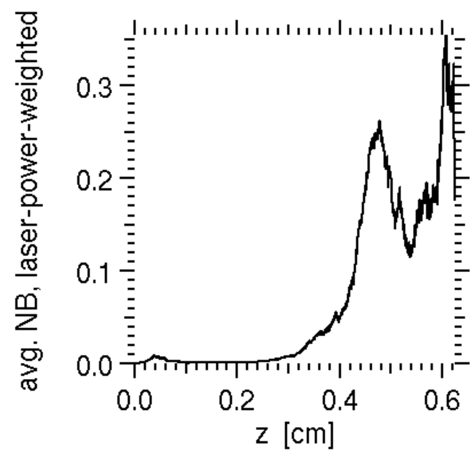


CH ablator case: conditions at run end (82.4 ps)

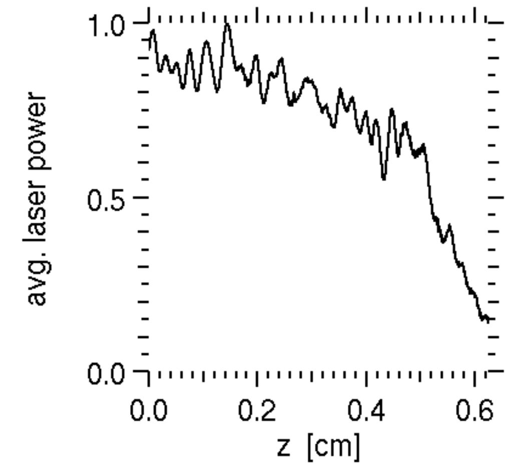
Bounce number, longitudinal plane



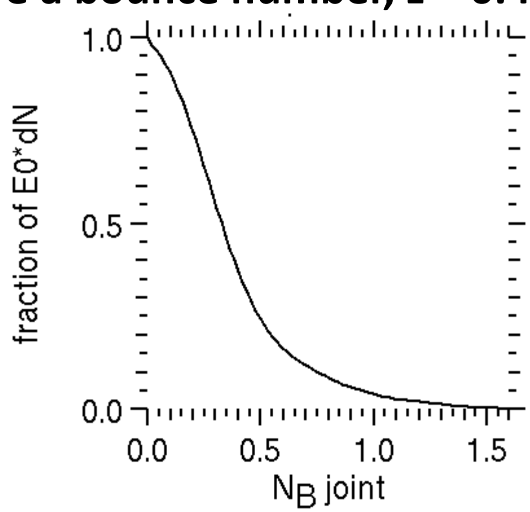
transverse-averaged bounce number (laser weighted)



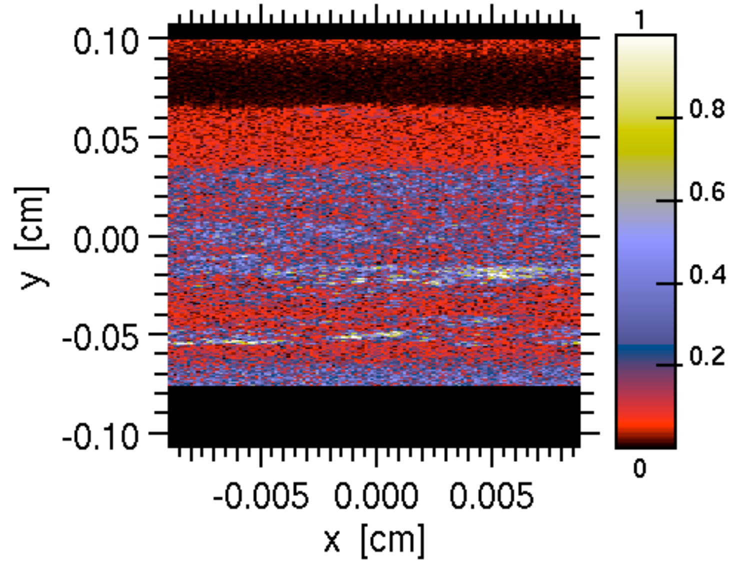
transverse-averaged laser power (a.u.)



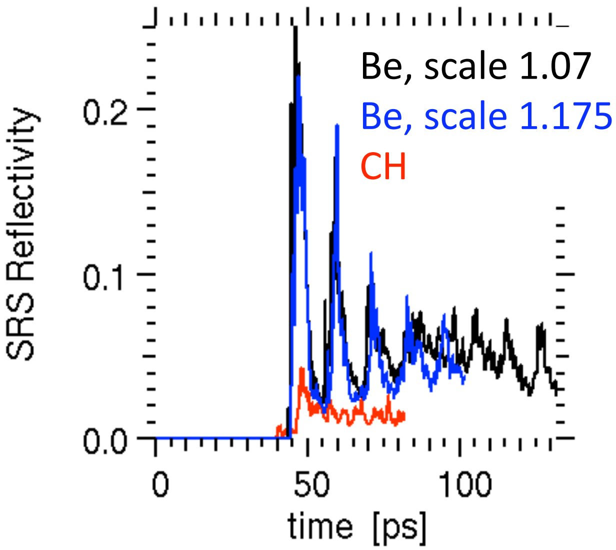
Fraction of scattered coupling (E_{las}•δn*) above a bounce number, z = 0.47 cm



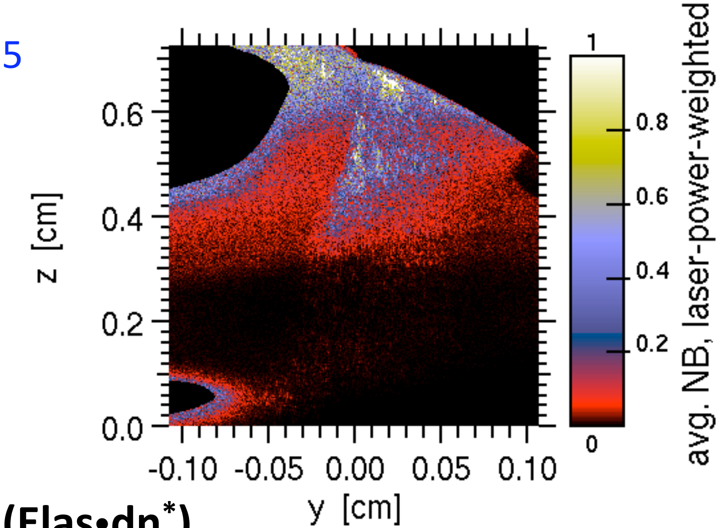
Bounce number at z = 0.47 cm

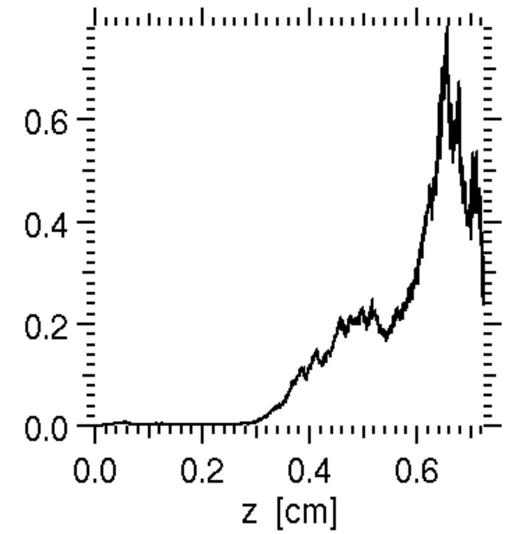


Comparison of CH and Be ablators: more SRS, and more trapping risk, in Be

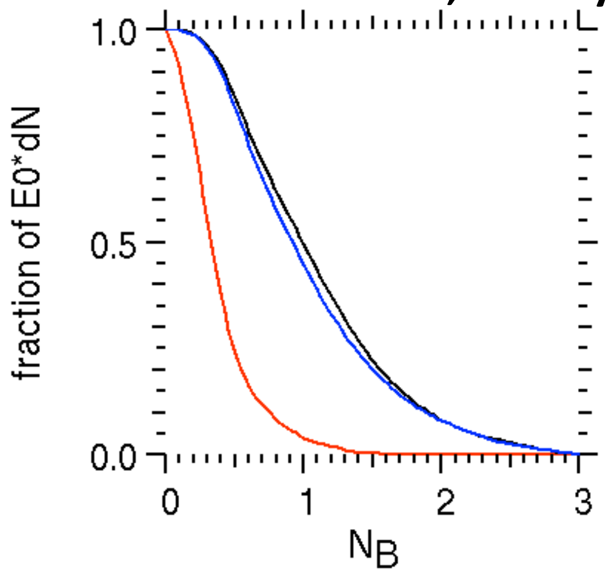


Bounce number   Be scale 1.07, time = 101 ps

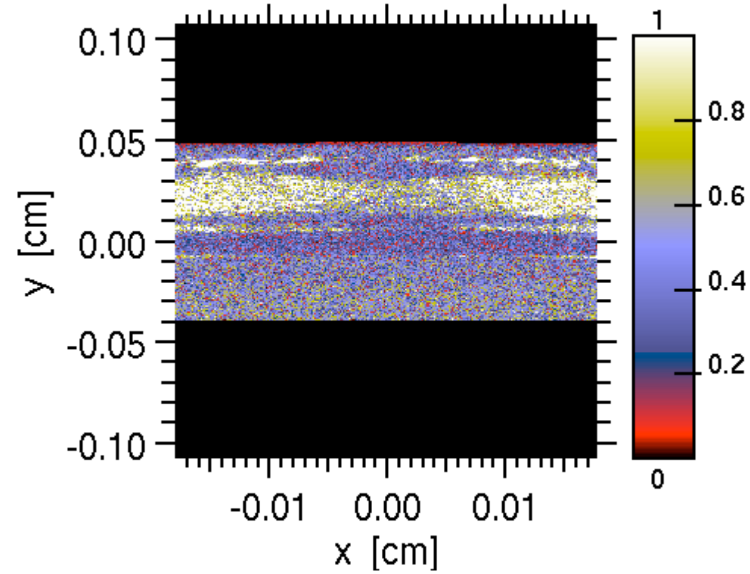




Fraction of scattered coupling (Elas•dn*) above a bounce number, over xy plane



Bounce number at z = 63 cm

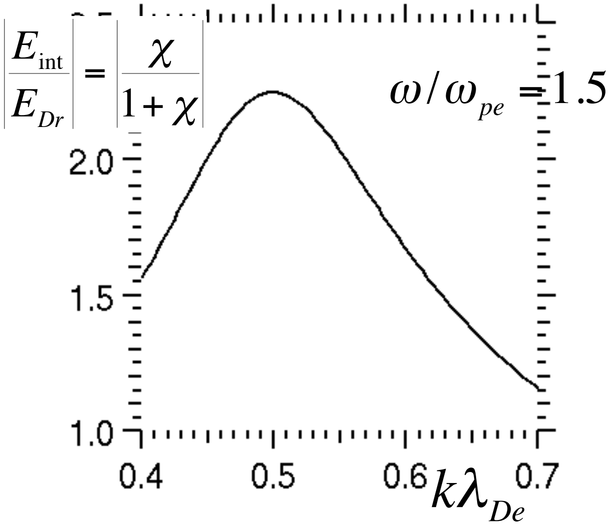


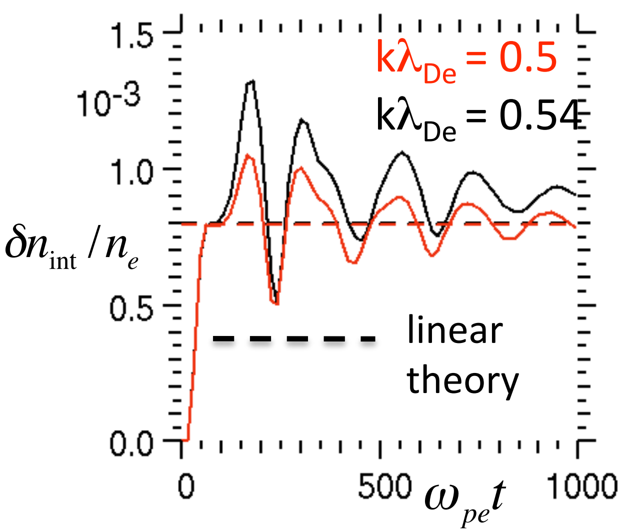
Summary and Future Work

- "Bounce number" provides a simple assessment of whether electron trapping nonlinearity can overcome detrapping processes (sideloss, collisions).
  - Sideloss is usually the domainant 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 $N_B >> 1$

"Resonance" is broad, not that high



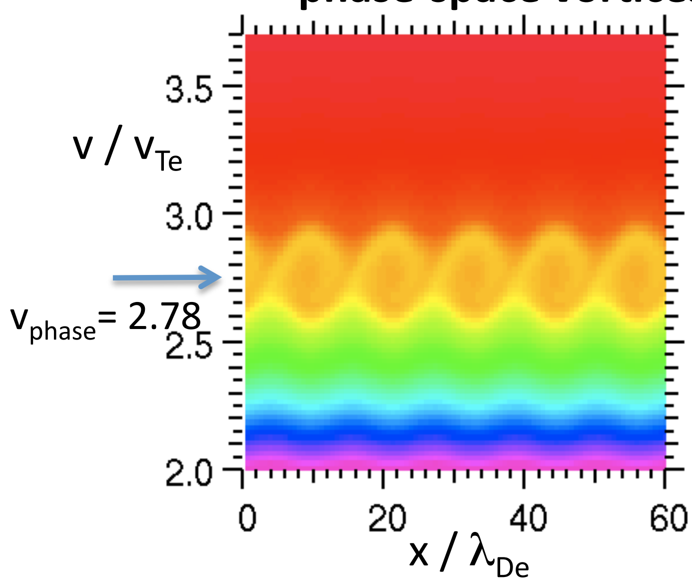


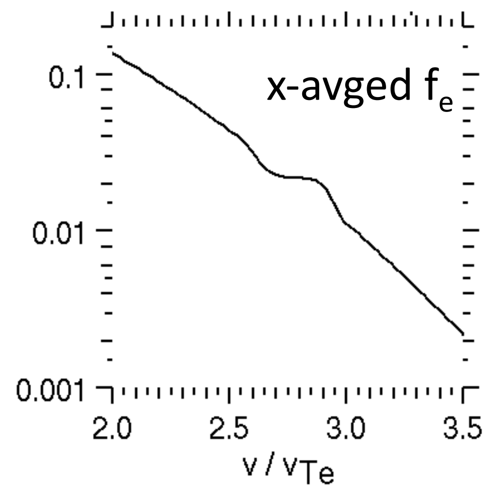
Homogenous, periodic plasma:
n_e/n_{crit} = 0.07 T_e = 5 keV;
ν_{Krook} = 4.3E-4ω_{pe} (sideloss for L_{perp}=100 um)

Krook relaxation: $\partial_t f \,|_{Krook} = \nu_K \cdot \left(n\hat{f}_0 - f\right)$

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 ω_{pe} = 750: phase-space vortices; x-avged f flattened





[1] S. Brunner, E. J. Valeo, PRL 93, 145003 (2004).

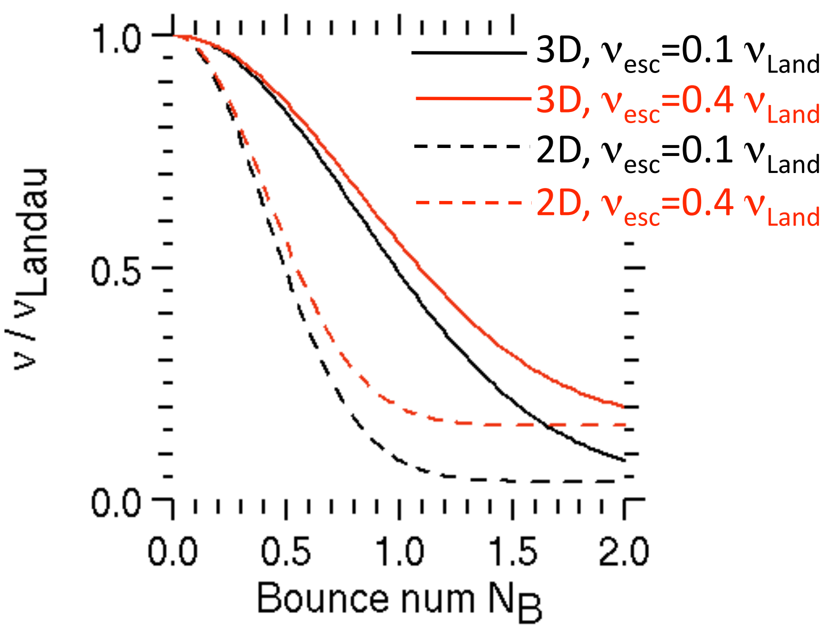
Reduced model by H. Rose, for Langmuir waves of finite transverse size

damping reduction: $\frac{\nu}{\nu_{\text{Landau}}} = f + 0.4(1-f)\frac{\nu_{\text{esc}}}{\nu_{\text{Landau}}}$ $\quad f = \exp\left[-\ln 2 \cdot \left(\frac{2\pi}{3(D-1)}\right)^2 \mathrm{N}_B{}^2\right]$ D = dimensionality = 2,3

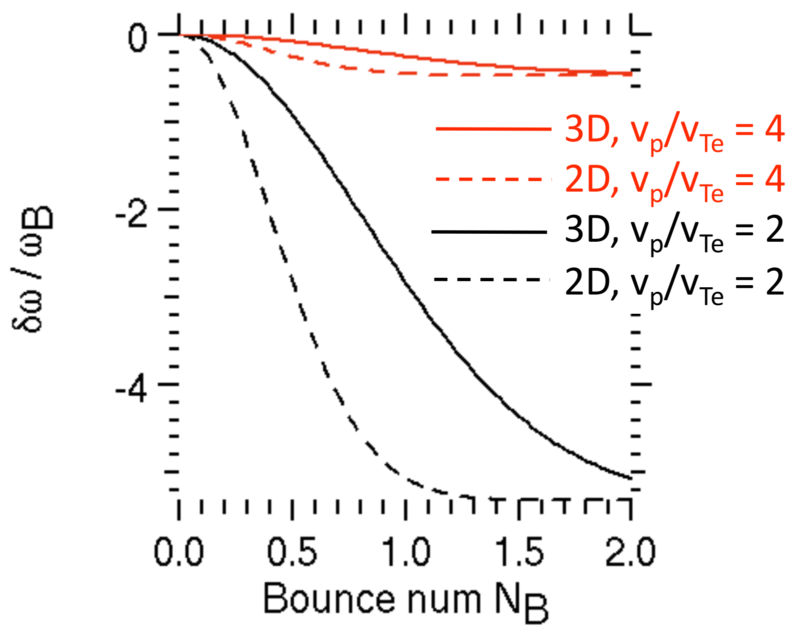
frequency shift: $\frac{\delta\omega}{\omega_B} = -0.88\left(\frac{v_p}{v_{Te}}\right)^3 f_{mxw}''(v_p/v_{Te})\cdot(1-f)$ $\quad \frac{\nu_{\text{esc}}}{\nu_{\text{Landau}}} \sim \frac{v_{Te}}{L_\perp}$ Depends on $k\lambda_D$, 2D/3D

Benchmarked by transit-time damping and PIC calculations.

Damping Reduction: more rapid in 2D than 3D



Frequency Downshift: rapidly increases with $k\lambda_D$



DEPLETE[1] performs ray-based, steady-state backscatter calculations

Pump:

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

Scattered Light:

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

inv. brems. damping | brems. source | Thomson scattering | SBS/SRS coupling

The code DEPLETE does:

- use 1-D plasma conditions from 3-D ray-trace
- handle a spectrum of scattered frequencies
- use a strong damping limit plasma-wave
- deplete the laser pump
- use Thomson scatter/bremsstrahlung noise sources
- inverse-bremsstrahlung light wave damping
- use linear kinetic coupling coefficients
- include collisional damping of Langmuir waves
- model whole-beam focusing

The code DEPLETE does not:

- include temporal effects
- include laser speckle effects
- include multi-D effects

[1]D. J. Strozzi, E. A. Williams, D. E. Hinkel, D. H. Froula, R. A. London, D. A. Callahan, Phys. Plasmas 15, 102703 (2008).