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

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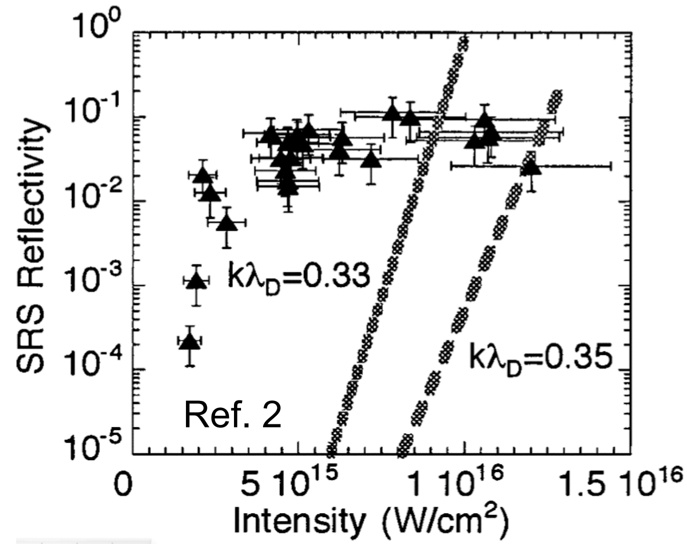
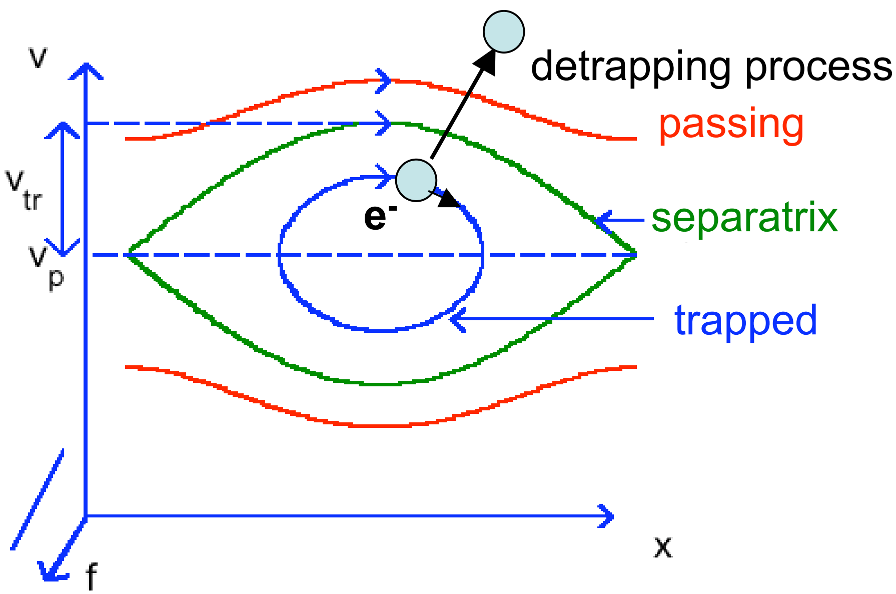
Electron trapping nonlinearities in SRS have attracted significant attention in recent years

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).

[1] H. X. Vu, D. F. DuBois, and B. Bezzerides; PRL **86**, 4306 (2001); [2] D.S. Montgomery et al., Phys. Rev. Lett. **87**, 155001 (2001);
[3] G. J. Morales and T. M. O'Neil, PRL 28, 417 (1972); [4] D. Bénisti, D. J. Strozzi, L. Gremillet, PoP **15**, 030701 (2008);
[5] J.L. Kline et al., PRL **94**, 175003 (2005); [6] S. Brunner and E. J. Valeo, PRL **93**,145003 (2004); [7] L. Yin, B. J. Albright, et al., PRL **99**, 265004 (2007);
8 H. A. Rose and L. Yin, PoP 15, 042311 (2008)

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

Bounce number[1]:

$$N_B \equiv \frac{\tau_{de}}{\tau_B}$$

bounce orbits a resonant e- completes before it's detrapped.

Bounce period:

$$\tau_B \equiv \frac{2\pi}{\omega_{pe}} \delta N^{-1/2}$$

$$\delta N \equiv \delta n / n_e$$

Total detrapping time:

$$\tau_{de} \equiv 1/\nu_{de}$$

$$\nu_{de} \equiv \sum_i \nu_i$$

Sum rates for each detrapping process: probability e- detrapped in time dt = sum of prob. detrapped by each process

Bounce number for one detrapping process:

$$N_{Bi} \equiv \frac{1}{\tau_B \nu_i}$$

$$N_B^{-1} = \sum_i N_{Bi}^{-1}$$

bounce numbers add in reciprocal; dominated by fastest detrapping process

[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:

$$\partial_t f = \nu_K(\delta N) \cdot \left[n\hat{f}_0 - f \right]$$

$\hat{f}_0 =$ normalized Maxwellian

- e-folding decay time for a feature in f is $\tau_e = 1/\nu_K$.
- For collisional loss, effective ν_K depends on wave amplitude δN.

τ_e = detrapping time ⟶

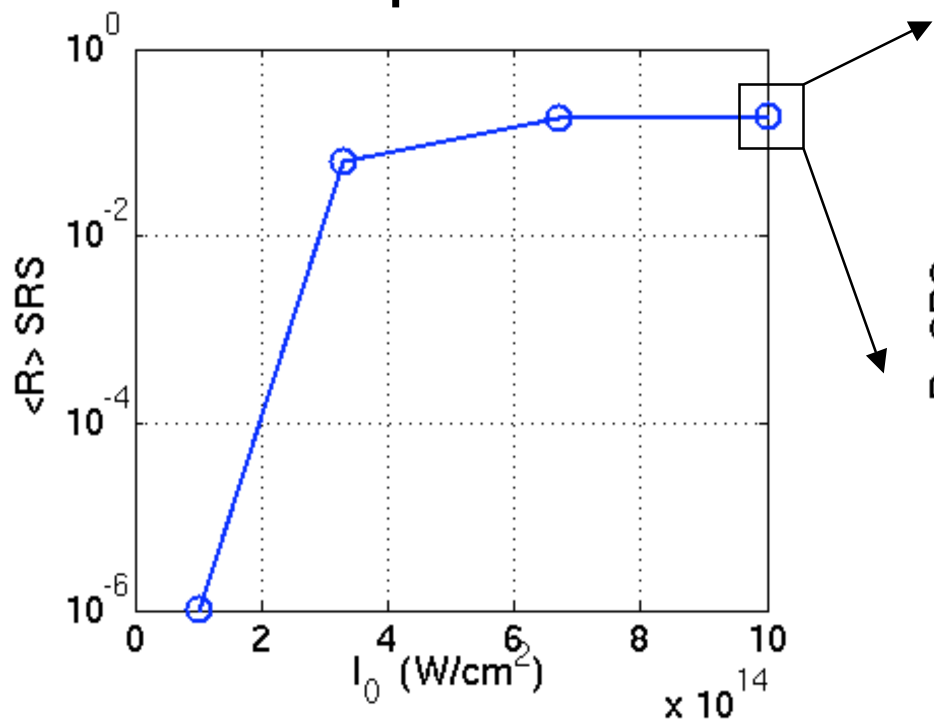
$$N_B = \frac{\tau_e(\delta N)}{\tau_B}$$

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**

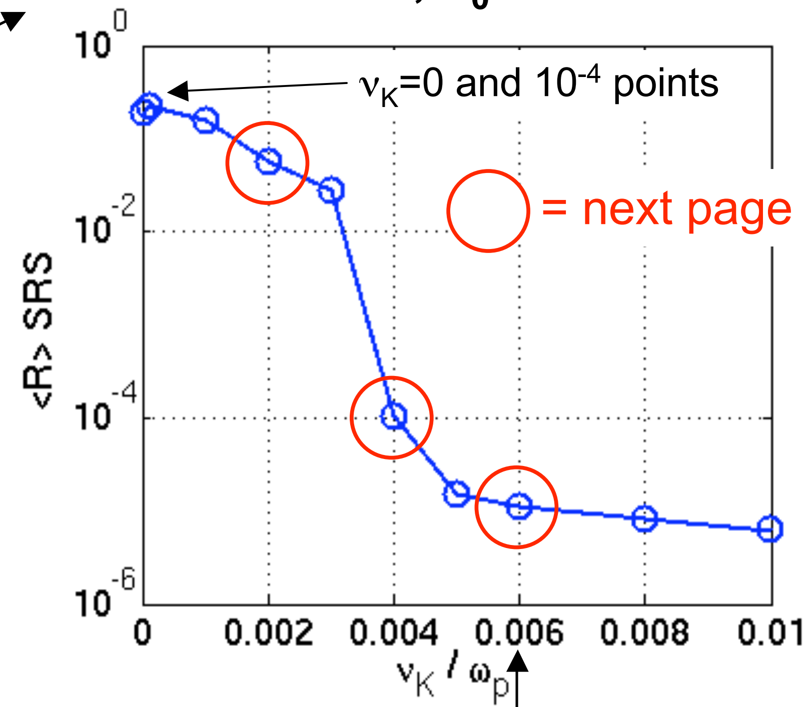
- "NIF inner SRS" parameters: $n_e/n_c = 0.115$, $T_e = 2.1$ keV; $k_{epw}\lambda_D=0.275$.
- Backscattered seed: $I_1/I_0 = 10^{-6}$; bandwidth $0.04\omega_p$.
- Focusing factor: FWHM = $181\lambda_0$ ($= 5F^2\lambda_0$ for F=6).

No Krook: Trapping threshold: speckle endloss



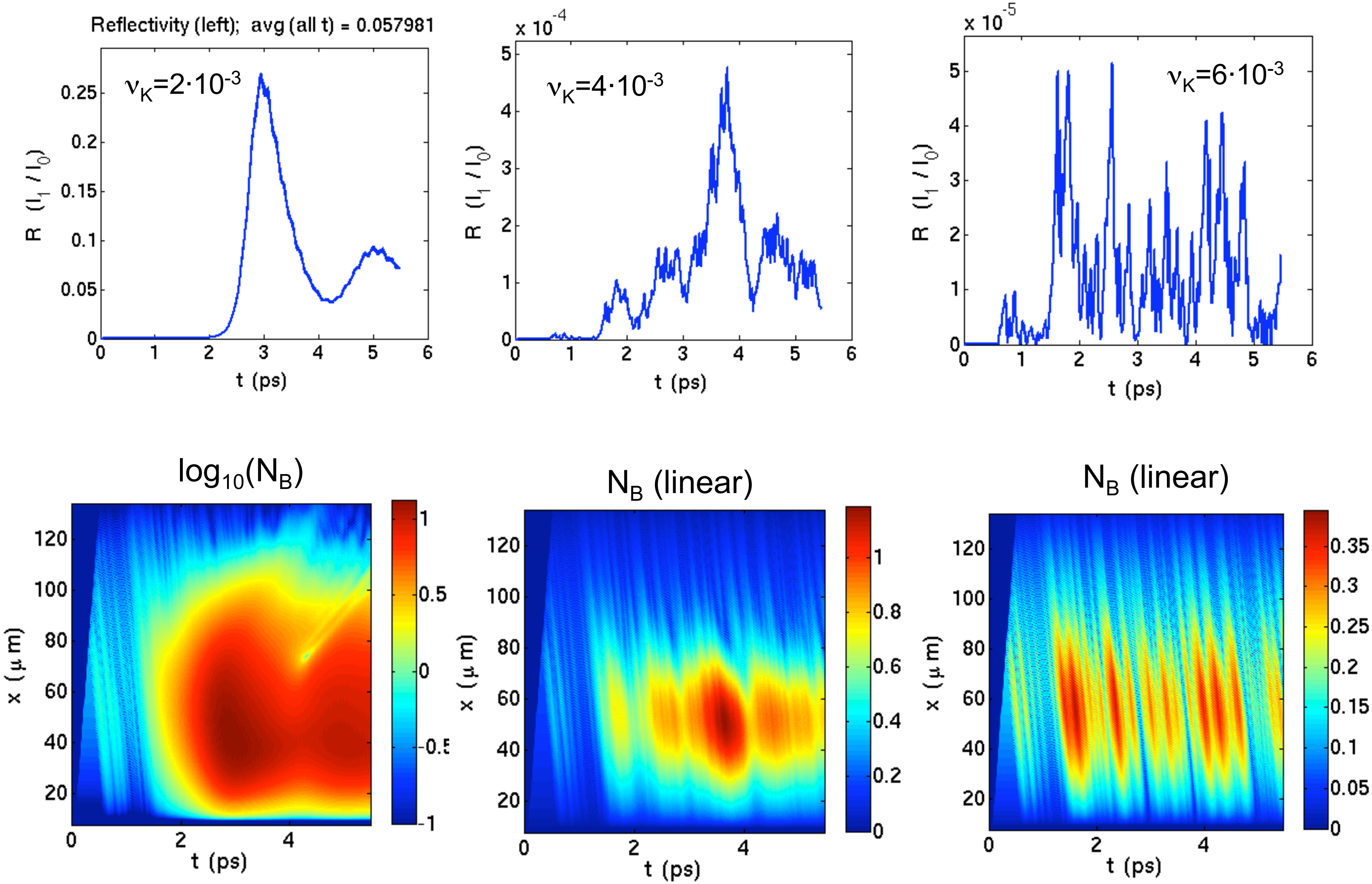
Absolute instability threshold: $I_{ab} = 2\cdot10^{15}$ W/cm^2

With Krook; $I_0=10^{15}$ W/cm^2



$\nu_{Landau} = 0.006\omega_p$

Time-dependent reflectivites and bounce numbers for “NIF inner SRS” parameters: N_B = 1 is a decent estimate for inflation



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: $\tau_{e2} = 0.88\ L/v_e$ 3D: $\tau_{e3} = 0.48\ L/v_e$ ← we use this below

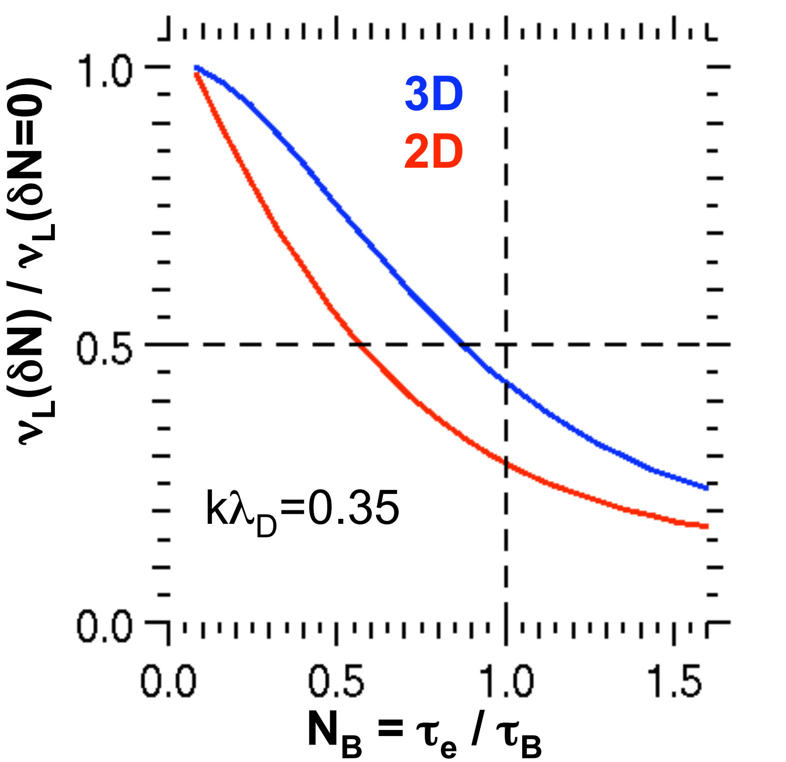
- Rose 3D calculations show, 50% reduction in transit-time damping for $\tau_{e3,tt} \approx L/v_e$.
- NIF example: F=8, λ_0=351 nm, τ_{e3}= 0.10 ps / $T_{e,kV}^{1/2}$

- Using τ_{e3} and $L = F\lambda_0$:

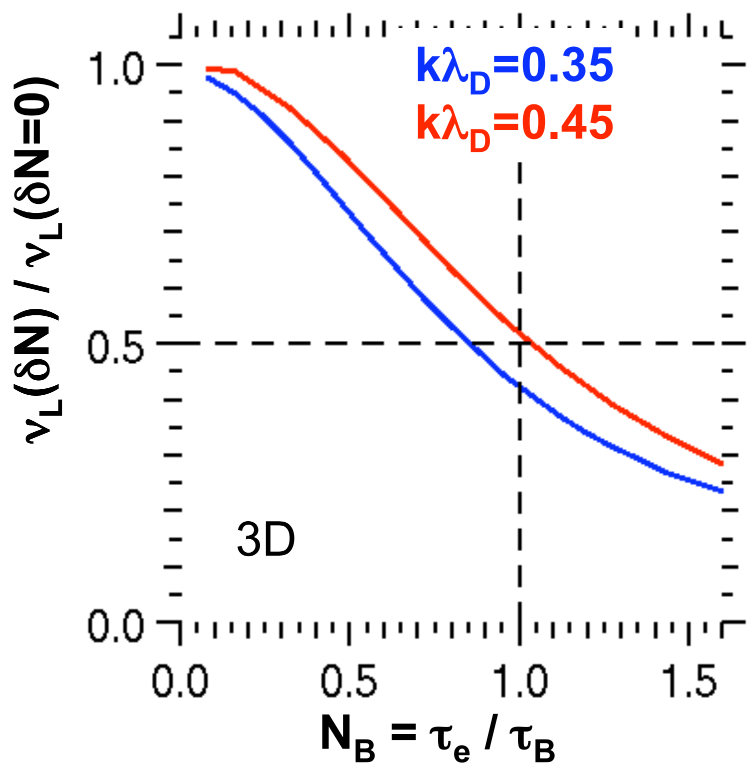
$$N_B = \frac{\tau_{e3}}{\tau_B} = \left[\frac{\delta N}{\delta N_{sl}}\right]^{1/2} \qquad \delta N_{sl} \equiv 1.33 \cdot 10^{-4} \left[\frac{8}{F}\right]^2 \frac{n_c}{n_e} T_{e,kV}$$

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 $k\lambda_D$



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

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

Electron-electron and electron-ion collisions provide a threshold, which we compute in a unified way

- Collision operator: $$\partial_t f = \nu_{ei}\partial_\mu\left[(1-\mu^2)\partial_\mu f\right] + 2\nu_{ee}\frac{v_T^{\,3}}{v^2}\partial_v\left[f + \frac{v_T^{\,2}}{v}\partial_v f\right]$$

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

- Ed Williams analysis [prior talk]: time for half e- to escape:

$$\nu_{ei}(v = v_T)t_{1/2} = \left(k\lambda_D\right)^{-2} G\left[v_p/v_T, \hat{Z}\right]\cdot \delta N$$

- Detrapping rate (= e-fold time):

$$\tau_{coll} = \frac{t_{1/2}}{\ln 2}$$

- Bounce number:

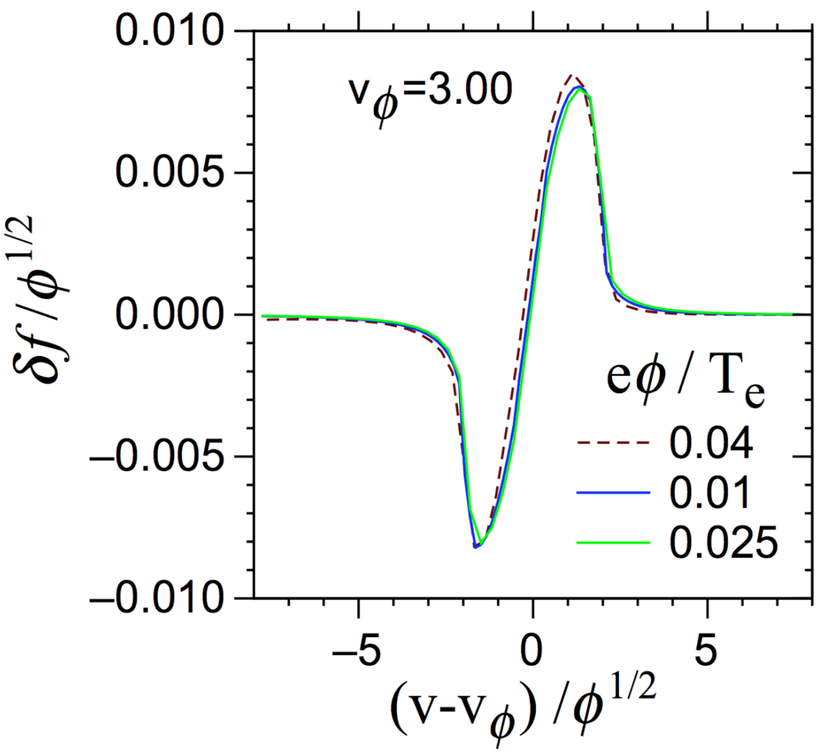
$$N_{B,coll} = \frac{\tau_{coll}}{\tau_B} = \left[\frac{\delta N}{\delta N_{coll}}\right]^{3/2} \qquad \delta N_{coll} \equiv \left[2\pi \ln 2\,\frac{\nu_{ei}(v = v_T)}{\omega_p}\frac{(k\lambda_D)^2}{G}\right]^{2/3}$$

Rose collisions analysis: e-e collisions weakly modify the transit-time (Landau) damping rate

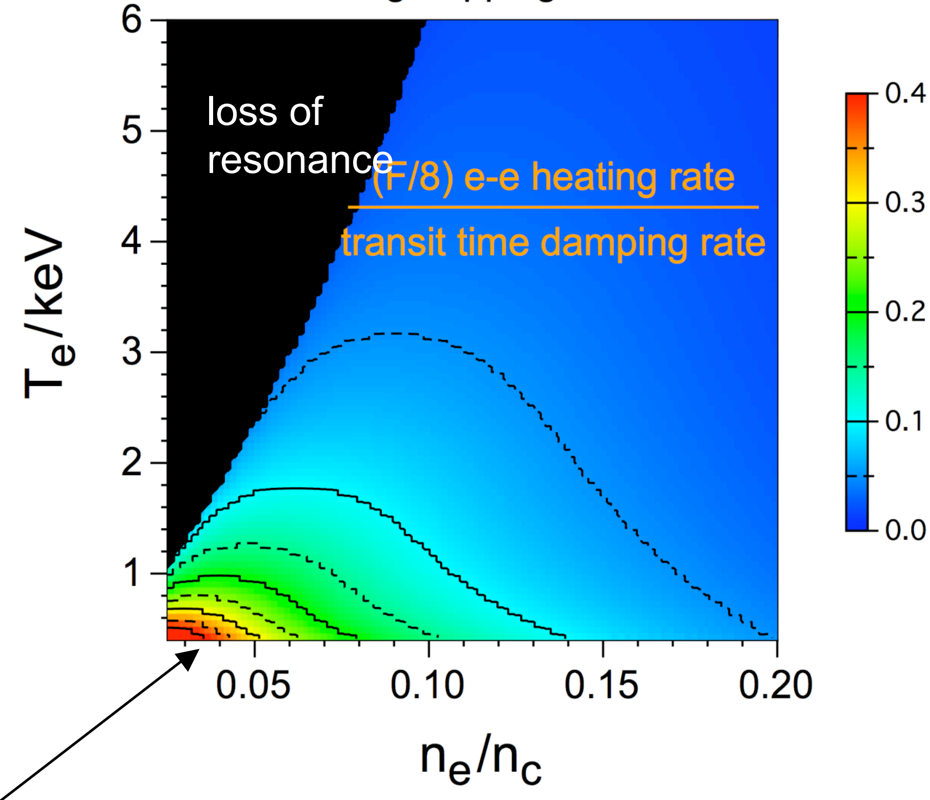
e-e collisions →

$$\frac{\frac{d(KE)}{dt}}{\text{Transit time damping}} \propto \frac{\nu_{\text{coll}} \times \phi^{3/2} \nu_{\text{Landau}}}{\nu_{\text{Landau}} \phi^2} \propto \frac{\nu_{\text{coll}}}{\sqrt{\phi}} \propto \frac{\nu_{\text{coll}}}{\omega_p} F \frac{\lambda_0}{\lambda_D}$$

Distribution for BGK mode, used to calculate heating rate



At strong trapping onset



When e-e heating rate ~ 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

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

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

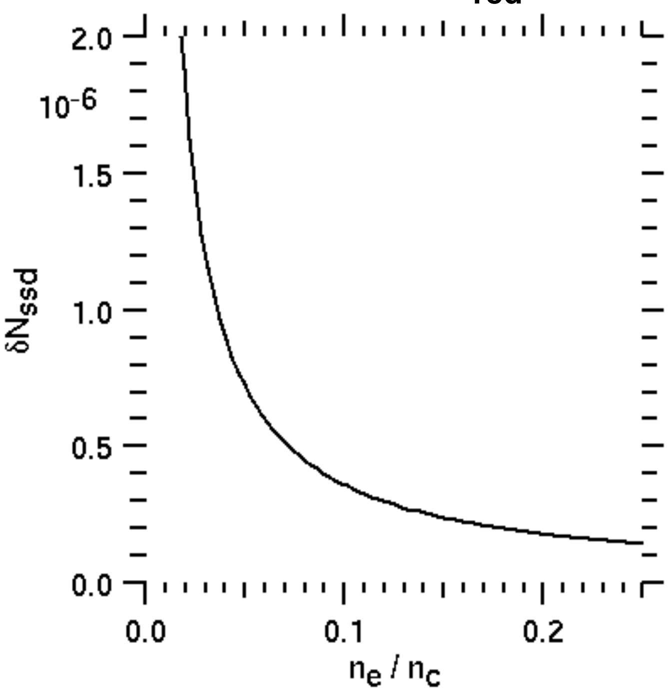
λ_{red} = 1054 nm

$$\tau_{ssd} \equiv \tau_{\mathrm{blue}} \frac{\lambda_{\mathrm{red}}}{\Delta\lambda_{\mathrm{red}}}$$

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

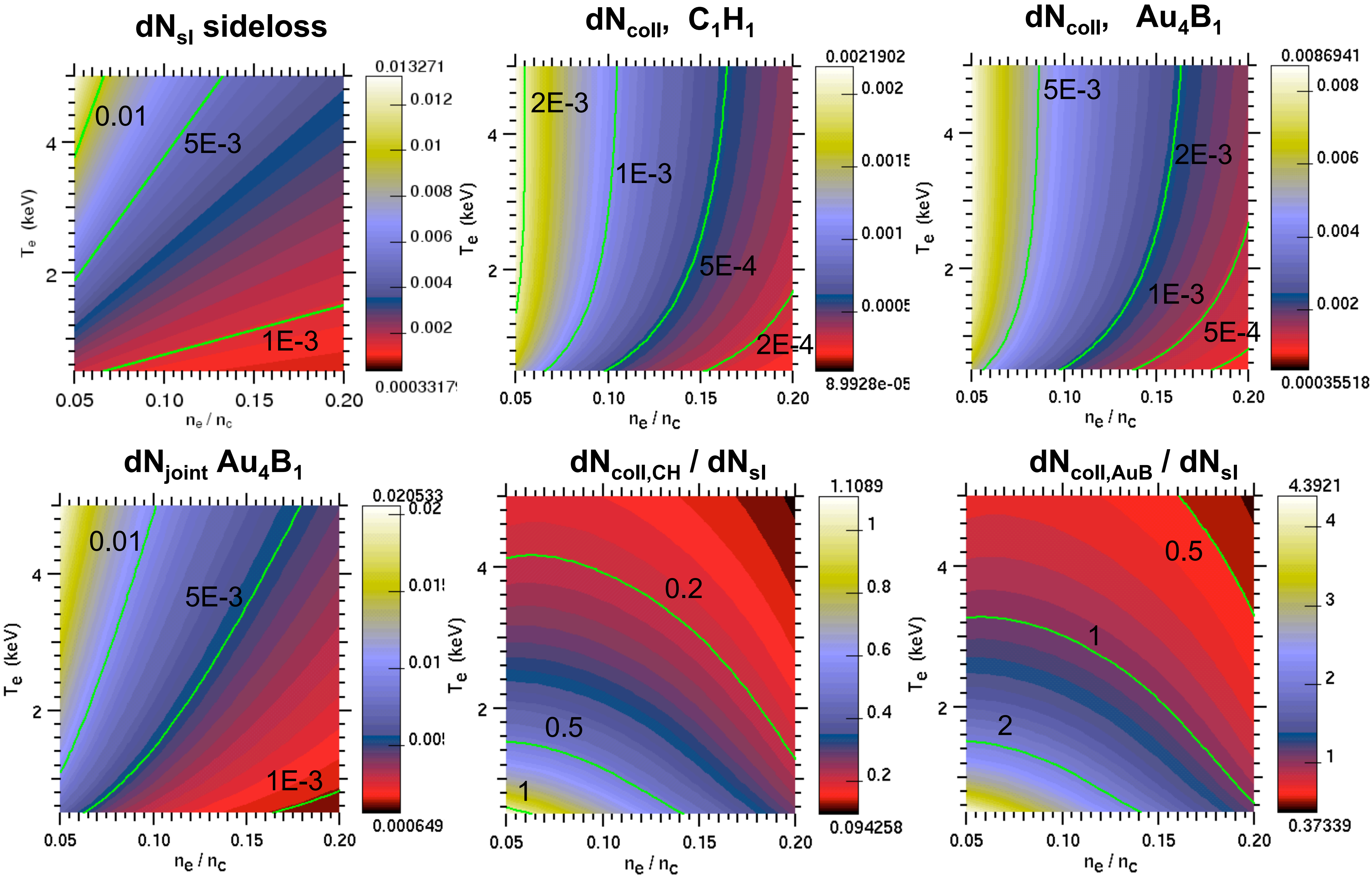
= 6.2 ps for $\Delta\lambda_{\mathrm{red}}$ = 2 Ang.

SSD threshold for $\Delta\lambda_{\mathrm{red}}$ = 2 Ang.

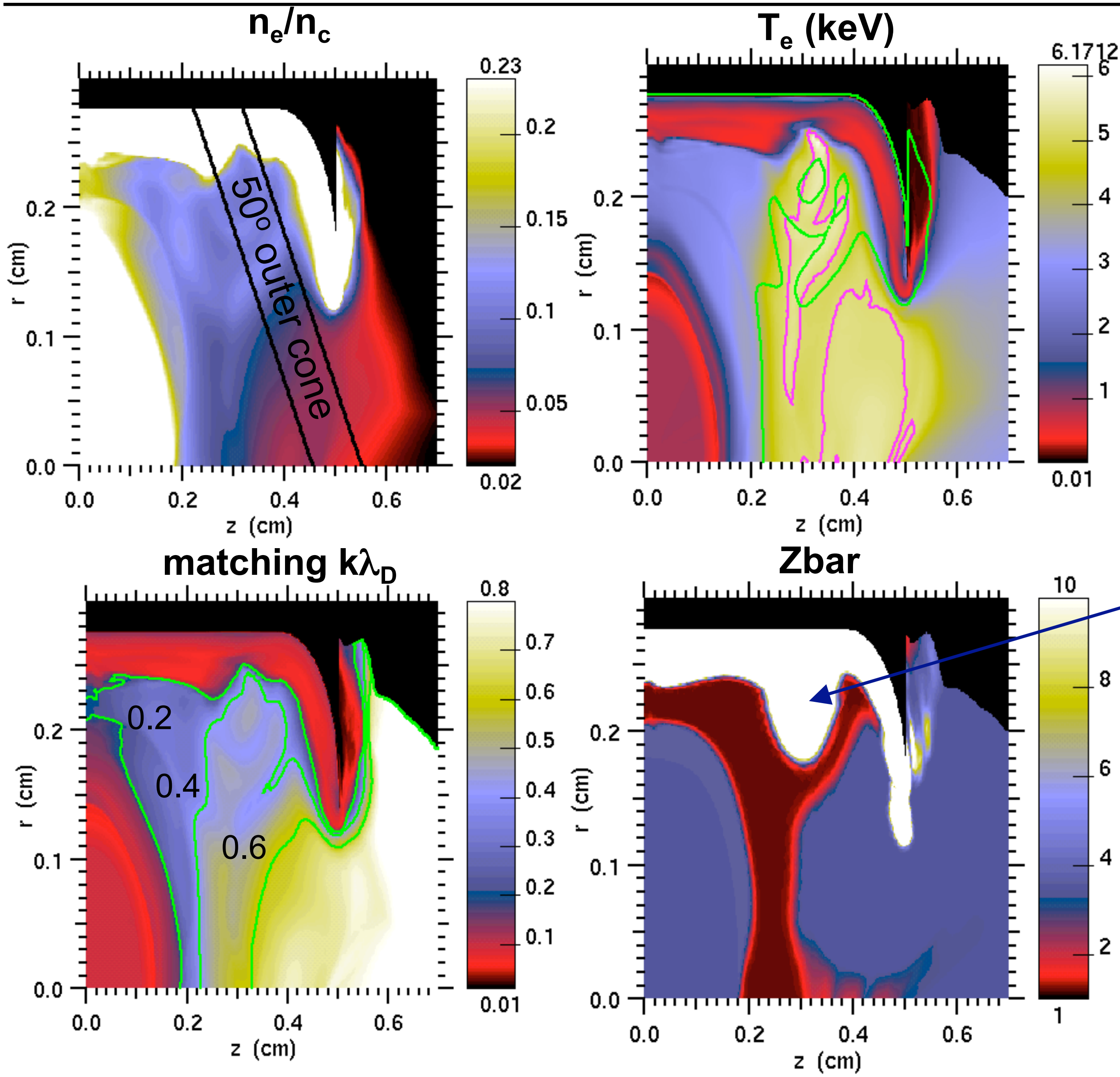


Much lower than thresholds due to sideloss or collisions.

Trapping threshold for sideloss usually dominant, but collisions can be larger in high-Z material



NIF design "test24": Rev 3, T_{rad} = 300 eV, CH ablator, at 15.5 ns (peak power)



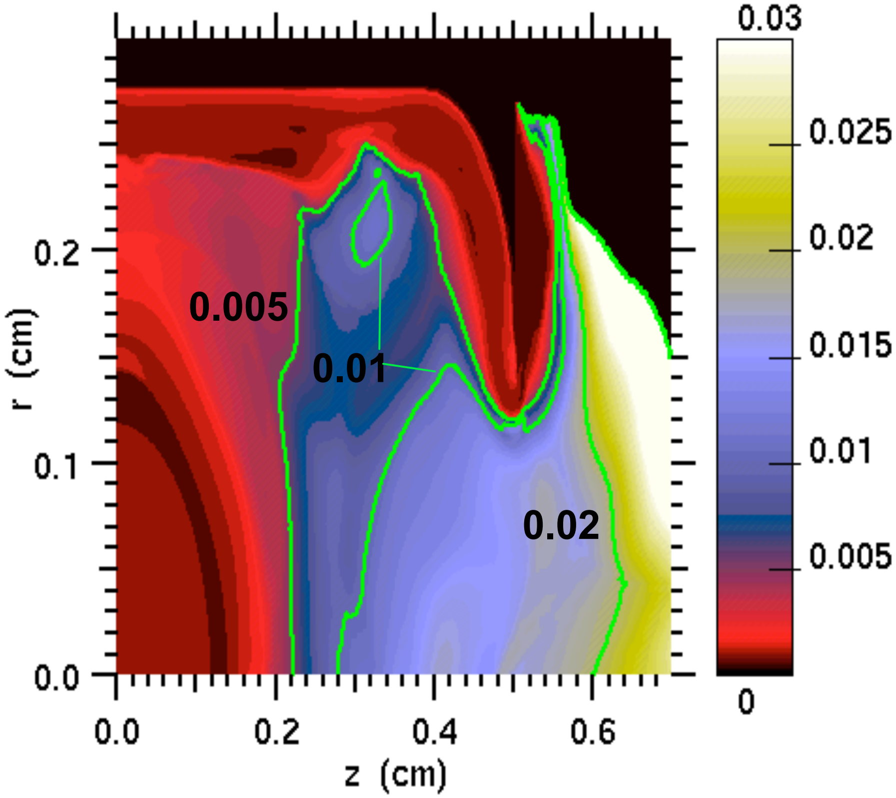
pF3D run: srs
matching: n_e=0.105n_c, T_e=5.2 keV
-> $k\lambda_D$=0.44

gold "bubble" due to outer beam

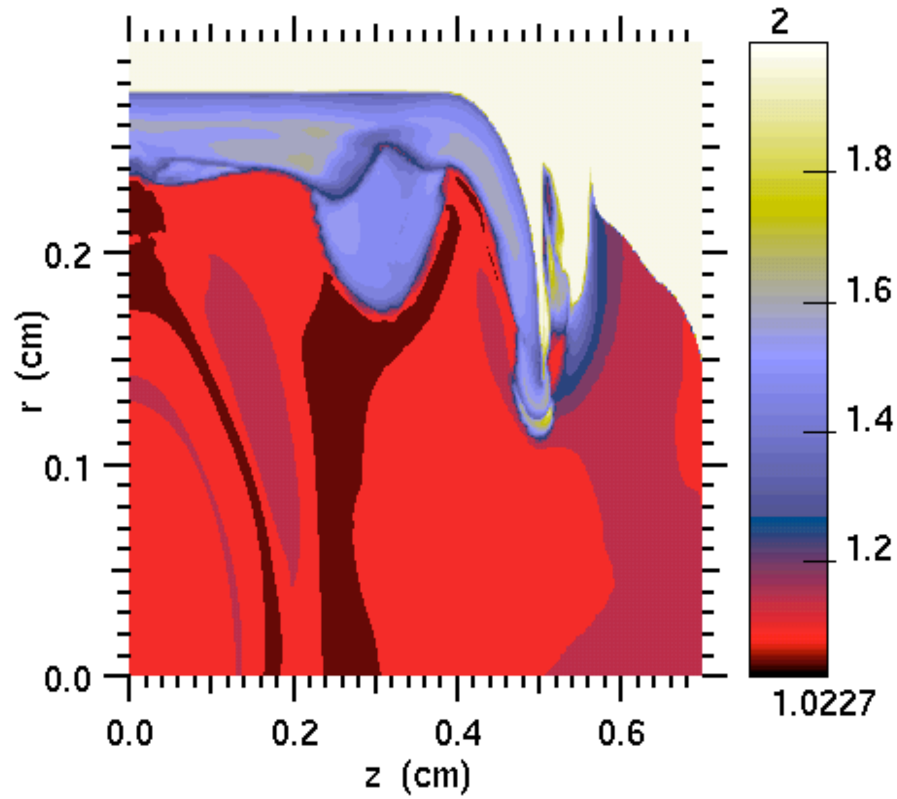
Design by D. Callahan (LLNL)

“test24” (300 eV, CH ablator): collisions matter for threshold in high-Z material

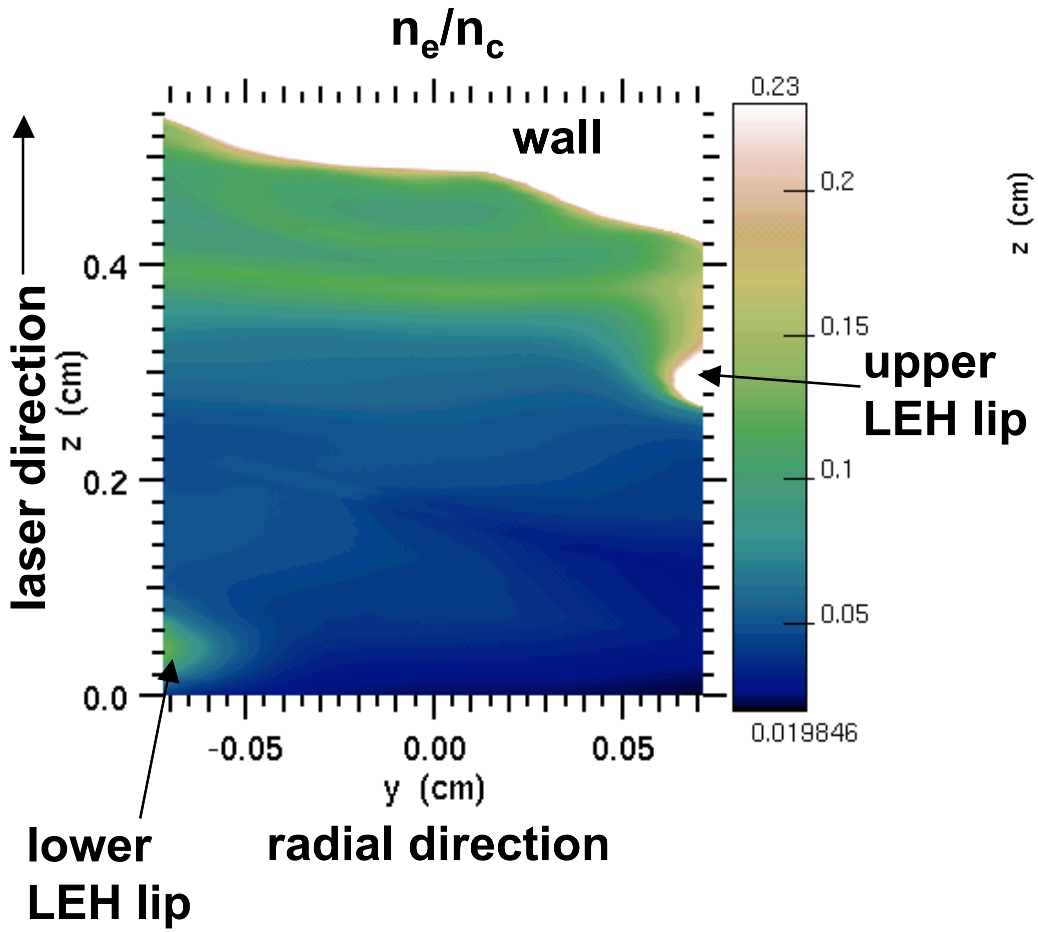
δN_{joint} (sideloss+collisions)

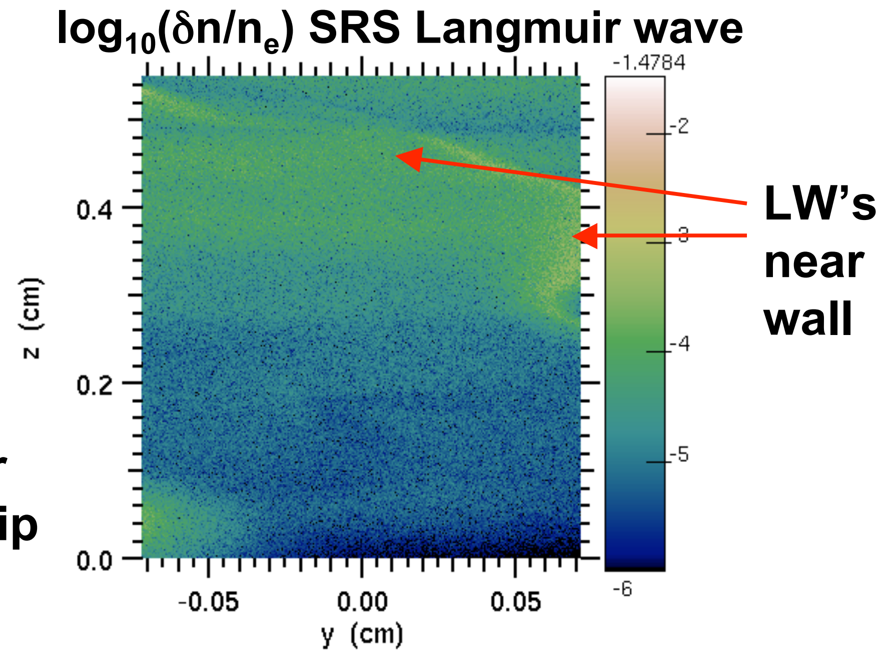


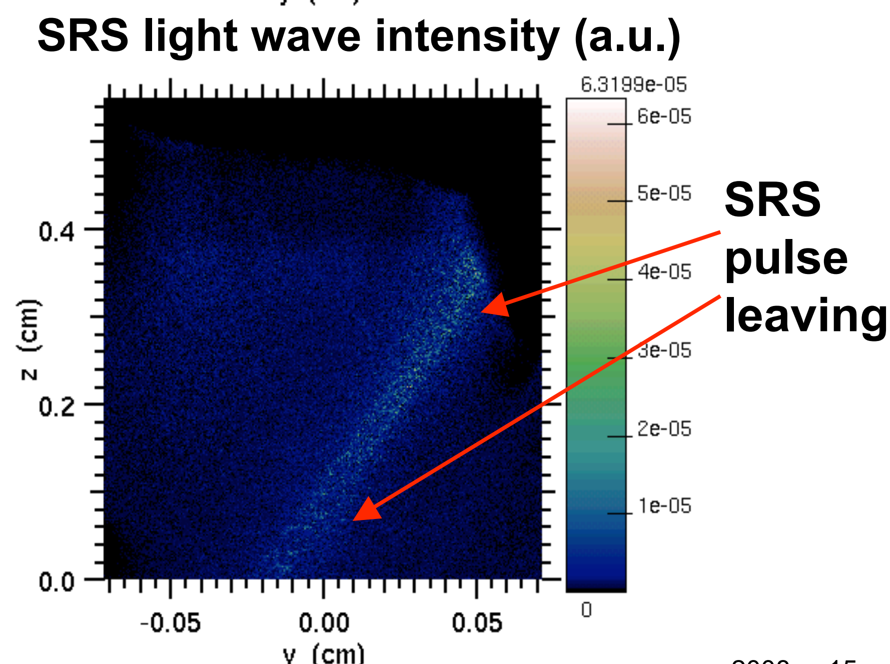
$\delta N_{joint} / \delta N_{sideloss}$:
sideloss within 2x of joint threshold



pF3D backscatter simulation on 50° cone of “test24” design: full beam path length and

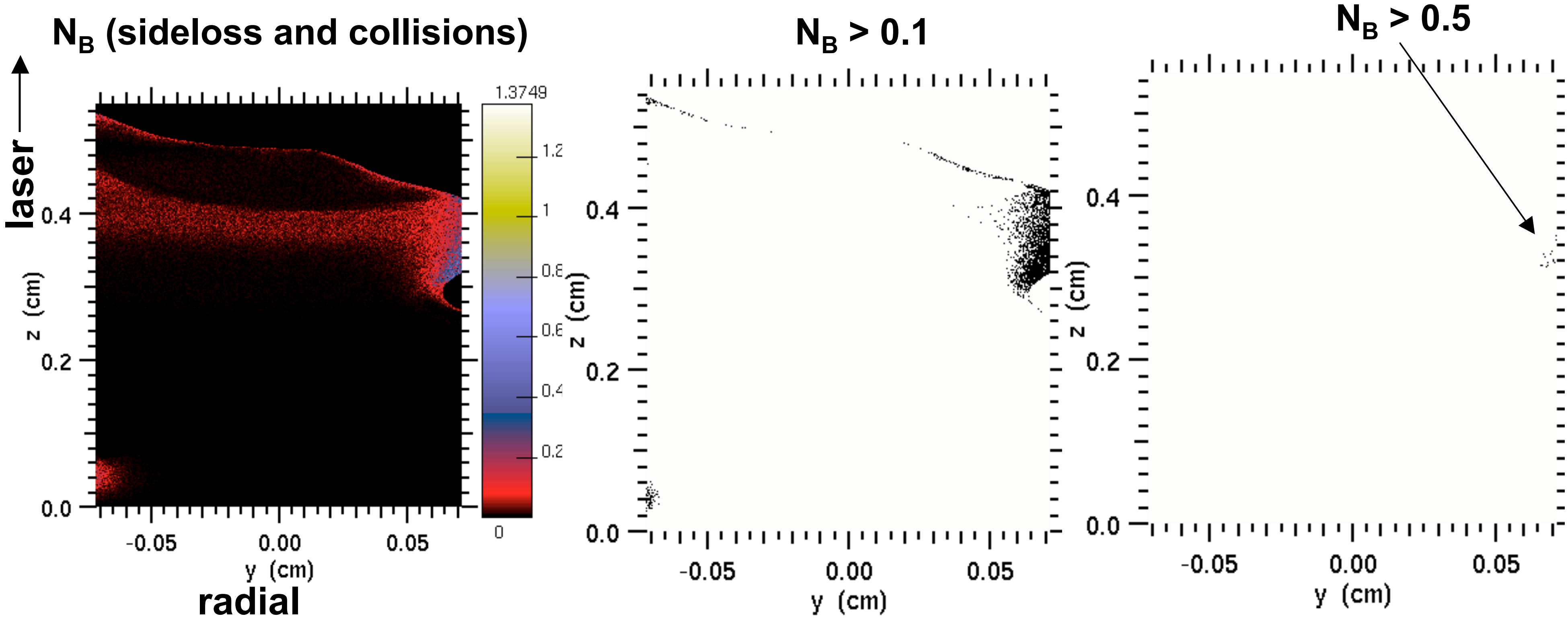






pF3D run “tg50t24_l01”

pF3D 50° cone run: bounce number well below threshold of ~ 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:** ≈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 $\delta n/n_e > 5 \cdot 10^{-3}$.
  - 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