# DEPLETE - a code for rapid assessment of backscatter activity

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**37th Anomalous Absorption Meeting**
**27 August 2007**

**Work supported by U.S. Department of Energy under Contract W-7405-Eng-48.**
**UCRL-PRES-233924**

# Hierarchy of Laser-Plasma Interaction (LPI) codes

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DEPLETE calculates the laser and backscattered intensities, in steady state, along a 1-D ray profile. It solves for a set of scattered-wave frequencies, with physical noise and pump depletion. Kinetic formulas are used for coupling and Thomson.

Compute power (log scale) ↓

- NEWLIP (E. A. Williams) - linear kinetic gain calculation along 1-D ray profile; steady-state.
- DEPLETE - Like NEWLIP, but solves for pump and scattered intensities with 1-D model of thermal fluctuations.
- SLIP (L. Divol, P. Michel) - 3-D, steady-state, kinetic coefficients.
- pF3D (D. Berger, C. H. Still, et al.) - laser propagation; enveloped laser and daughter waves; time evolution; 1-, 2-, or 3-D (patch, letterbox, whole beam, …).
- Kinetics (particle-in-cell, Vlasov) - full plasma physics (but small volumes).

# NEWLIP: finds linear backscatter gains for rad-hydro simulations; quick-and-dirty estimate

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- NEWLIP - Yorick code by E. A. Williams; finds gain $G(\omega_1)$ along many (~hundreds) of rays, to *quickly* assess target's backscatter risk.

$$\partial_s i_1(s,\omega_1) = -\alpha i_1 \qquad \alpha \equiv \frac{1}{4}\frac{f}{\eta_0}\frac{v_{os,0}^2}{c^2}\frac{k_2^2}{|k_{1p}|}\Im\frac{\chi_e(1+\chi_I)}{\epsilon}$$

**Solved for many $\omega_1$'s.**

s = distance along ray path;

$$I_1 = \int d\omega_1 i_1$$

$$\chi_I = \sum_{i=\mathrm{ions}} \chi_i \qquad \chi = \chi_e + \chi_I = \text{susceptibility} \qquad \epsilon = 1 + \chi = \text{dielectric}$$

- Plasma waves in the strongly-damped limit:

$$\frac{n_2}{n_e} = \frac{1}{2}\left|\frac{\chi_e}{\epsilon}\right|(k_2\lambda_{De})^2\frac{v_{os,0}v_{os,1}}{v_{Te}^2} \qquad n_{2e} = (1+\chi_I)n_2$$

- Linear gain:

$$i_1(s_L) = i_1(s_0)e^G; \qquad G \equiv \int_{s_0}^{s_L} ds\ \alpha(s)$$

G = linear intensity gain

**Linear gain G is the main "product" of NEWLIP.**

# DEPLETE equations: solve for pump and scattered intensities

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$$\partial_s I_0(s) = -\kappa_0 I_0 - \int d\omega_1 \frac{\omega_0}{\omega_1} I_0 \cdot (\tau_1 + \Gamma_1 i_1)$$ **pump laser**

$$\partial_s i_1(s,\omega_1) = \kappa_1 i_1 - \Sigma_1 - I_0 \cdot (\tau_1 + \Gamma_1 i_1)$$ **scattered light**

**inv. brem.** **brem. noise** **Thomson** **coupling**

**[all symbols positive]**

**Intensities are: [total power in ray] / [focal spot area].**

- **Bremsstrahlung:**

**inverse-brem. damping:** $\kappa_i \equiv \frac{\omega_{pe}^2}{\omega_i^2} \frac{\nu_{ei}}{v_{gi}}$

**brem. noise; $B_v$ = blackbody** $\Sigma_1 = f^{-1} \Omega_c \kappa_1 \frac{v_{gi}^2}{c^2} B_v$

- **Thomson:**

$$\tau_1 \equiv \frac{K_\tau}{|\epsilon|^2} \qquad K_\tau = \frac{\Omega_c}{\sqrt{2\pi}} n_e r_e^2 \frac{\omega_0}{\omega_{pe}} \frac{g_\tau}{k_2 \lambda_{De}} \qquad g_\tau \equiv |1+\chi_I|^2 e^{-\zeta_e^2} + |\chi_e|^2 \sum_i \frac{v_{Ti}}{v_{Te}} e^{-\zeta_i^2}$$

- **Coupling:**

$$\Gamma_1 = \frac{K_\Gamma}{|\epsilon|^2} \qquad K_\Gamma \equiv f \frac{2\pi r_e}{m_e c^2} \frac{1}{\omega_0} \frac{k_2^2}{k_{0p}|k_{1p}|} g_\Gamma \qquad g_\Gamma \equiv |1+\chi_I|\chi_{e,i} + |\chi_e|^2 \chi_{I,i}$$

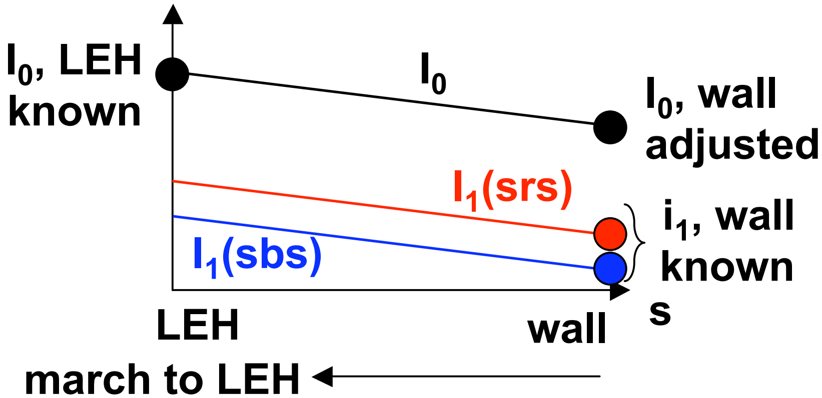
**scattered light F-cone:** $\Omega_c \equiv 2\pi(1-\cos\theta_c) \approx \frac{\pi}{4F^2}$

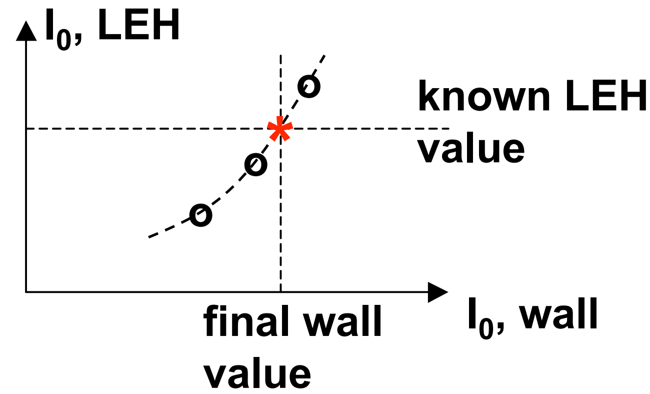
$$\cos\theta_c \equiv \left[1 + \frac{1}{4F^2}\right]^{-1/2} \approx 1 - \frac{1}{8F^2}$$

**whole-beam focusing:** $f \equiv \frac{\mathrm{area}(s)}{\mathrm{area}(s_{\mathrm{focus}})}$

# DEPLETE numerics: shoot on $I_0$ (s=wall), split step

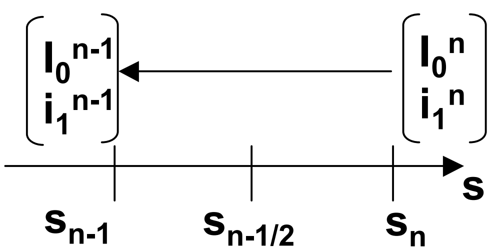
- Shooting: Two-point boundary-value problem. March from wall to LEH, varying $I_0$ (wall) until $I_0$(LEH) is close enough to known value.




Run time dominated by evaluating Z functions, not ODE solving (even with shooting).

- Split step:




$$[I_0, i_1]_{s_{n-1}} = B_{1/2} \cdot C_1 \cdot B_{1/2} \cdot [I_0, i_1]_{s_n}$$

$B_{1/2}$ = bremsstrahlung for a half-step:

$$\begin{aligned} \partial_s I_0 &= -\kappa_0 I_0 \\ \partial_s i_1 &= \kappa_1 i_1 - \Sigma_1 \end{aligned}$$

$C_1$ = coupling-Thomson for whole step:

$$\begin{aligned} \partial_s I_0 &= -\int d\omega_1 \frac{\omega_0}{\omega_1} I_0 \cdot (\tau_1 + \Gamma_1 i_1) \\ \partial_s i_1 &= -I_0 \cdot (\tau_1 + \Gamma_1 i_1) \end{aligned}$$

# Coupling-Thomson step: Analytical solution for narrow resonances

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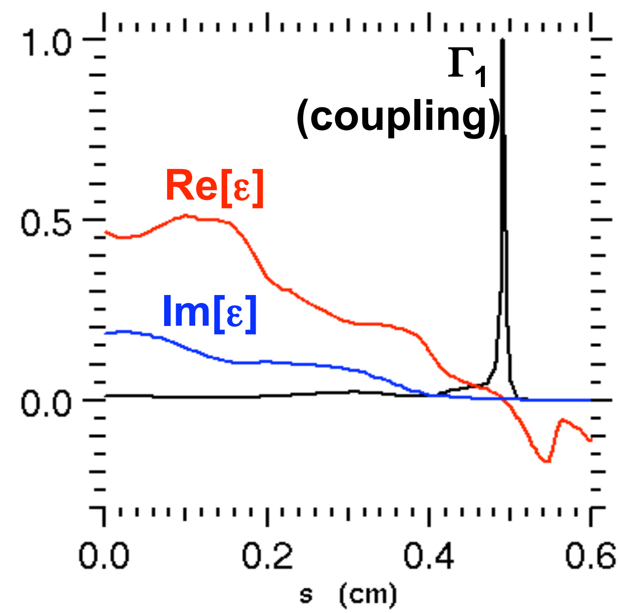
**Coupling-Thomson step over a single s cell: hold $I_0$ constant, solve for $i_1$ for every $\omega_1$, then update $I_0$ conservatively (Manley-Rowe).**

$$\partial_s i_1 = -I_0 \cdot (\tau_1 + \Gamma_1 i_1)$$

$$\Gamma_1 = \frac{K_\Gamma}{|\epsilon|^2} \qquad \tau_1 \equiv \frac{K_\tau}{|\epsilon|^2}$$




- **Problem:** **narrow resonances in coupling and Thomson coefficients hard for standard ODE solvers (e.g. Runge-Kutta).**

- **Solution:** **The resonance occurs when Re[ε] = 0 in the denominator; ε itself varies slowly, so linearize ε in a cell and analytically solve.**

$$\epsilon \approx \epsilon^{n-1/2} + \partial_s \epsilon^{n-1/2} \cdot (s - s_{n-1/2})$$

$$\partial_z i_1 = -\frac{B_\tau + B_\Gamma i_1}{1+z^2} \longrightarrow \begin{aligned} i_1^{n-1} &= (i_1^n + \beta) e^{B_\Gamma \Delta\omega} - \beta \\ \beta &\equiv B_\tau / B_\Gamma \\ \Delta w &\equiv \mathrm{atan}(z_n) - \mathrm{atan}(z_{n-1}) \end{aligned}$$

$$z \equiv \frac{s - \bar{s}}{L_s}$$

**E. A. Williams uses a similar technique for finding gains in NEWLIP (“`ratint`”).**

# Properties of DEPLETE



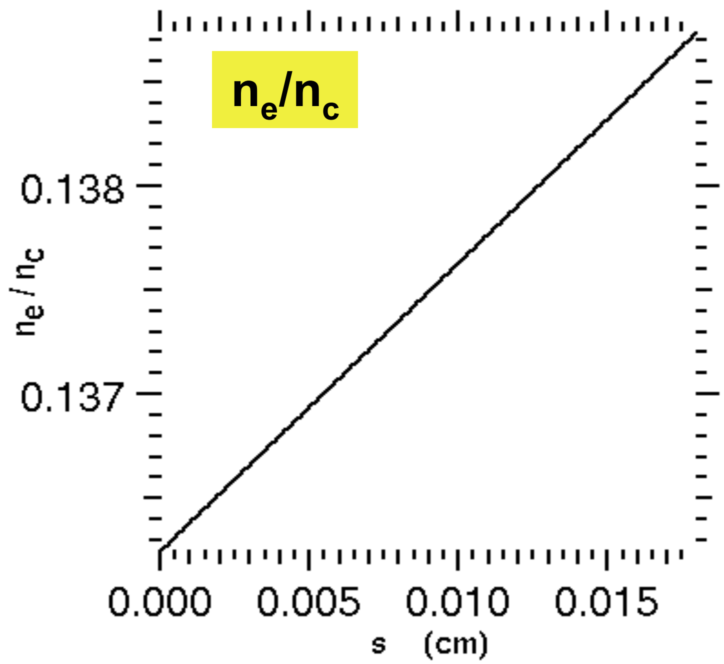
- Fast! Almost as fast as NEWLIP. Most time spent evaluating kinetic Z functions.
- Works along 1-D ray profiles (rad-hydro usually treats lasers via rays).
- 1-D noise: 3-D bremsstrahlung noise taken over beam F-cone.
- Gives scattered-wave intensities:
  – Measurable, unlike gain.
  – Allows for assessment of nonlinearities (e.g. trapping, LDI, inflation).
  – Re-absorption of scattered waves done.
- Pump depletion included.
- Kinetic description - same as NEWLIP, better than pF3D (some fluid approximations).
- Different scattered frequencies $\omega_1$ handled simultaneous:
  – No enveloping around a carrier wave, as in pF3D.
  – Different $\omega_1$'s treated incoherently (no spectral leakage; physical?).

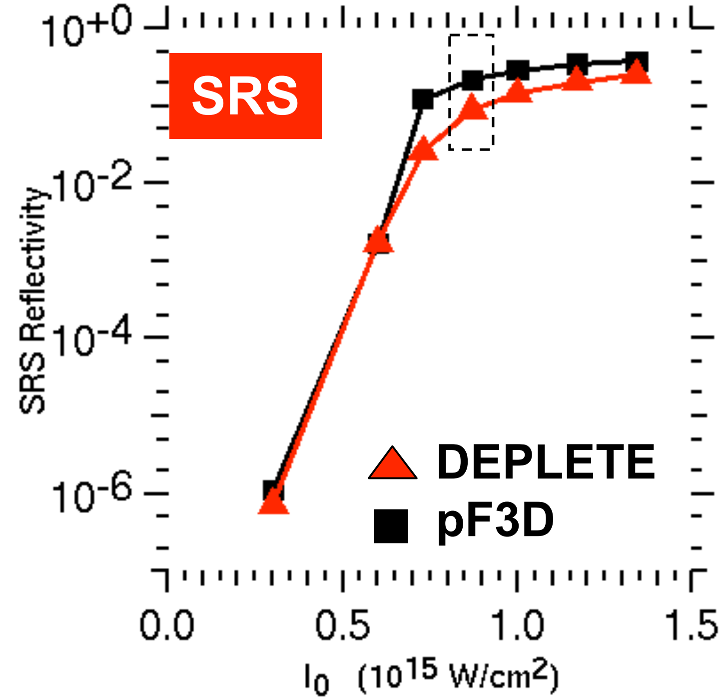
- DEPLETE lacks some physics in pF3D:
  – Steady-state - no time evolution.
  – 1-D: no transverse gradients, beam intensification.
  – no speckle physics, no beam smoothing (but we have ideas).
  – no plasma-wave advection (strong damping limit).
  – DEPLETE model not strictly valid for absolute instability.

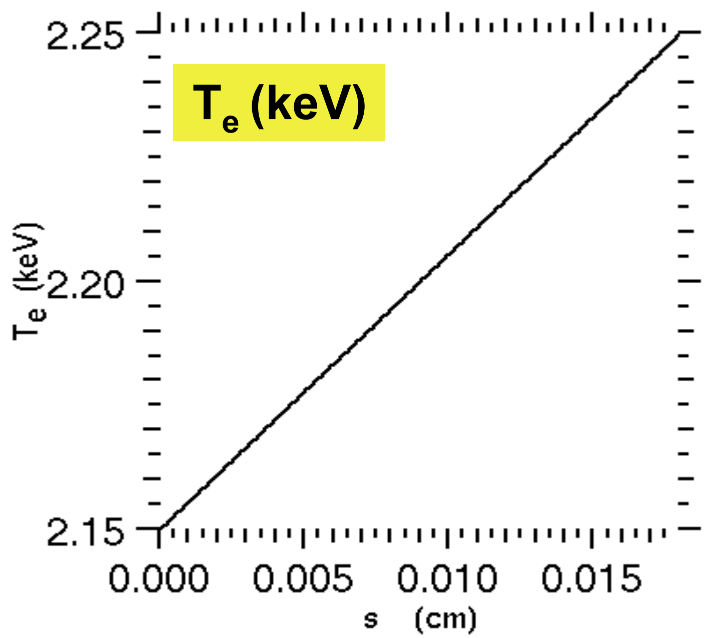
# Tests of DEPLETE on "clean" profile: linear gradients, just SRS

"clean"

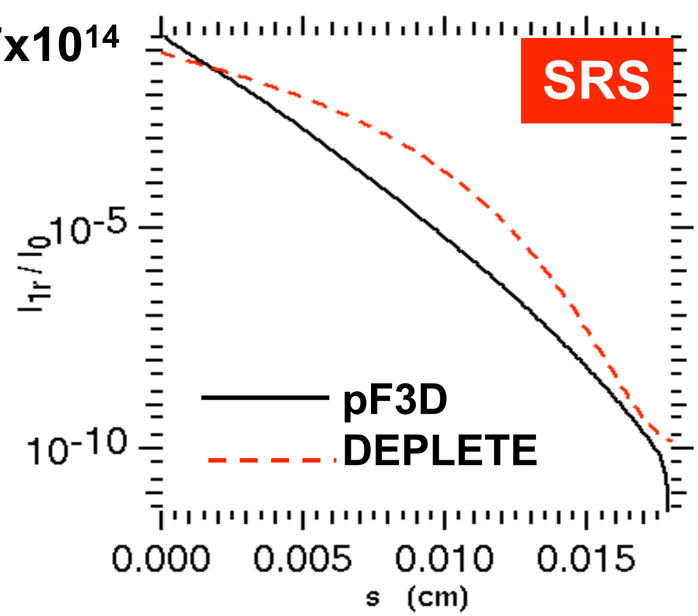
**pF3D run: 3-D plane wave; no transverse pump structure like speckles.**




$I_0 = 8.7 \times 10^{14}$



# "Clean" profile test: scattered-light spectrum from pF3D and deplete have similar shape

"clean"

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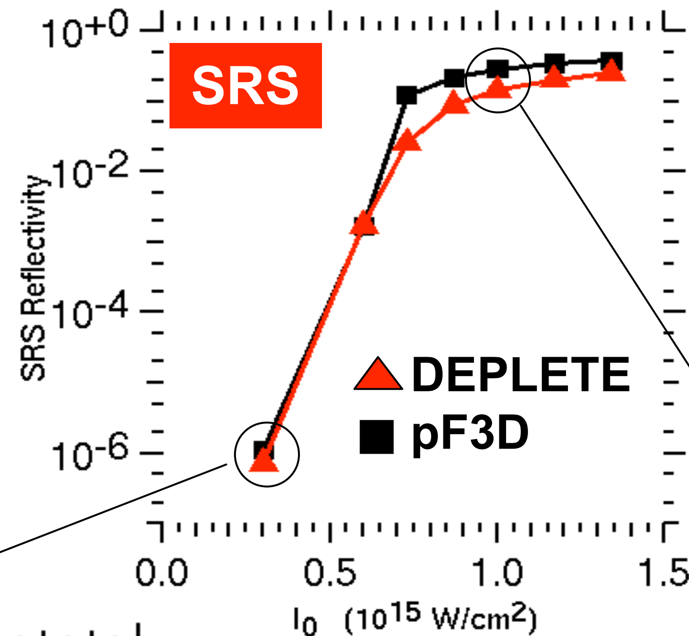
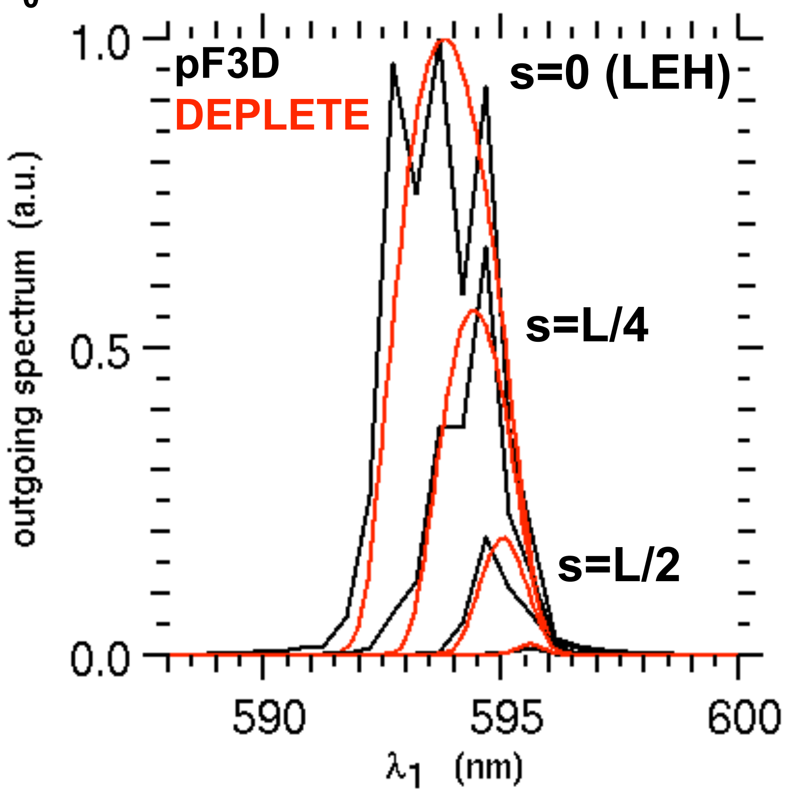


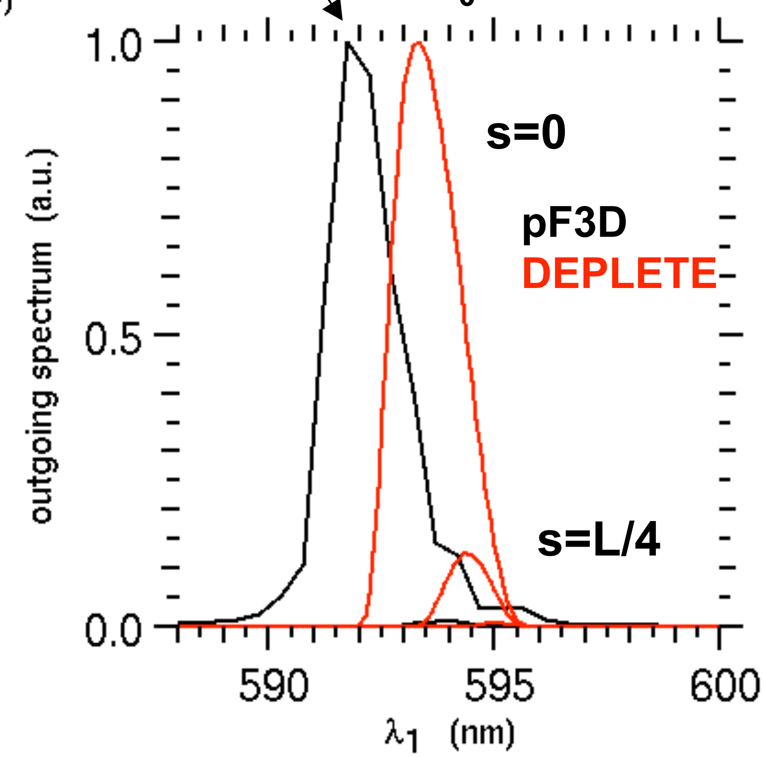

In the linear regime, the spectra are quite similar.

In the saturated regime, pF3D has more pump depletion, less scattering from high density.

$I_0 = 3\times10^{14}$




$I_0 = 1.17\times10^{15}$

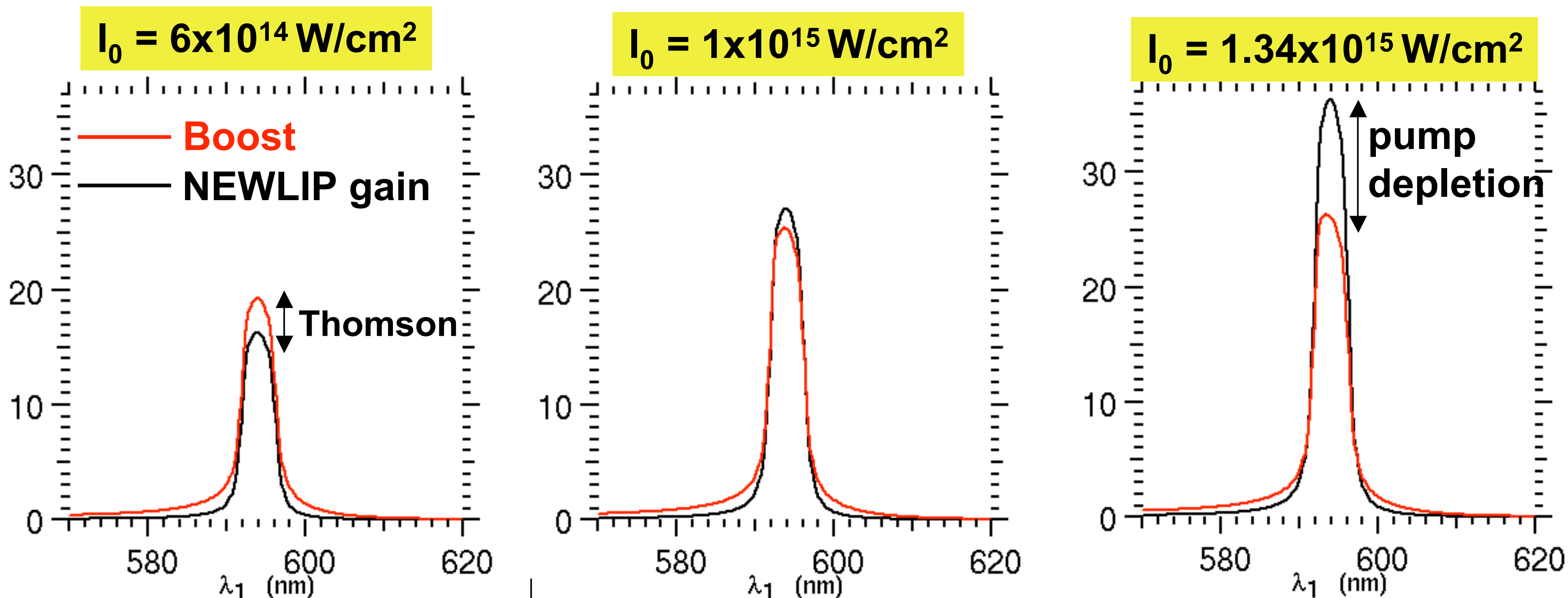


# “Clean” profile test: NEWLIP gain vs. DEPLETE boost

“clean”

- Increases confidence in gain, and is a “sanity check” on DEPLETE.
- But NEWLIP doesn’t give intensities.

$$\text{DEPLETE “Boost”} = \log\left[\frac{\text{scattered spectrum with brem., Thomson, and coupling}}{\text{scattered spectrum with just bremsstrahlung (i.e. no laser)}}\right] = \frac{\text{“backscatter”}}{\text{“noise”}}$$




**Boost > gain due to Thomson**

**Boost < gain due to pump depletion (and some absorption)**

# Sample profile: inner beam (23 deg.) Be ray, 270 eV point design at time of peak laser power

270V Be

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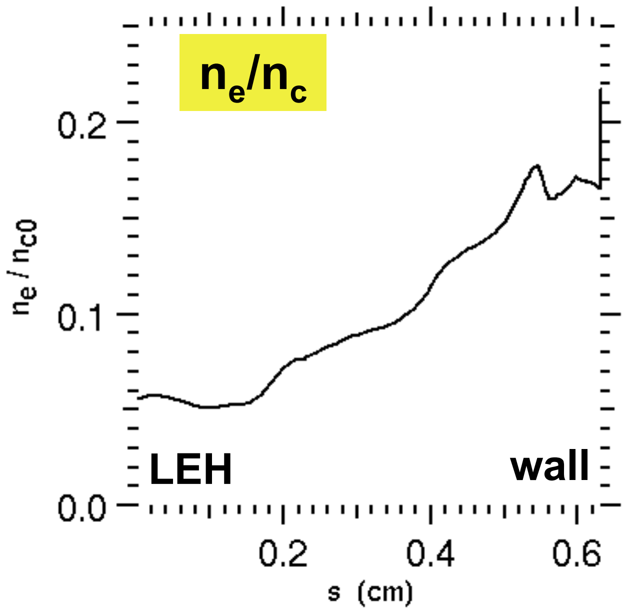


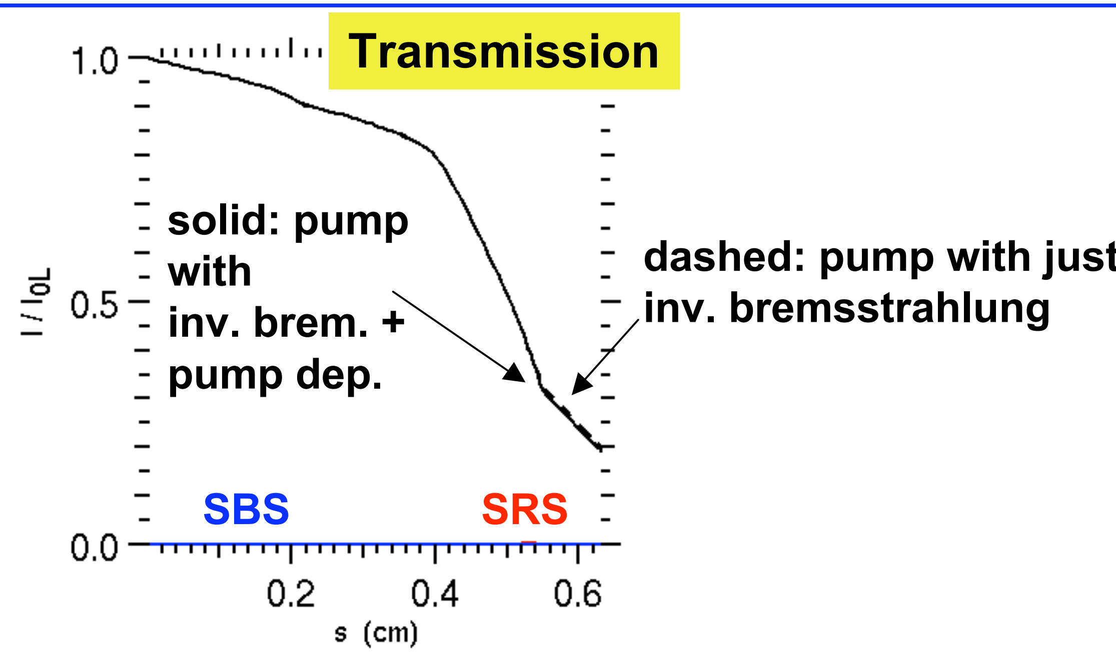


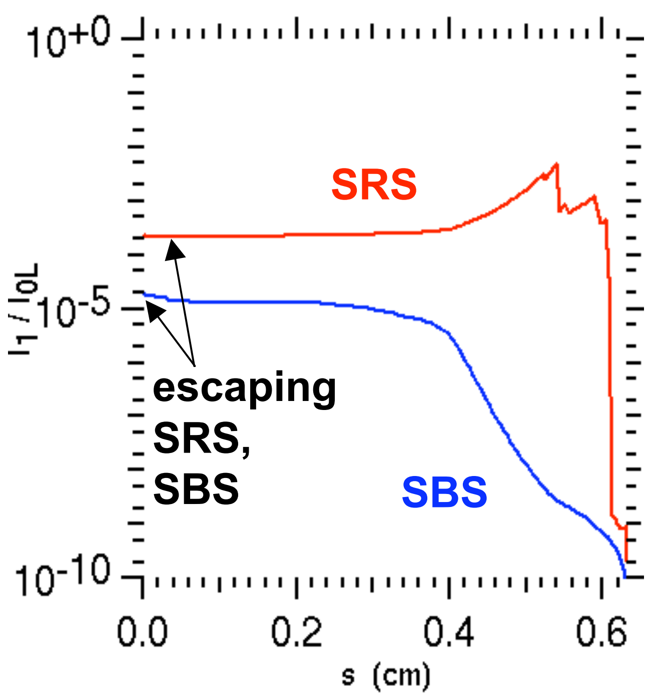


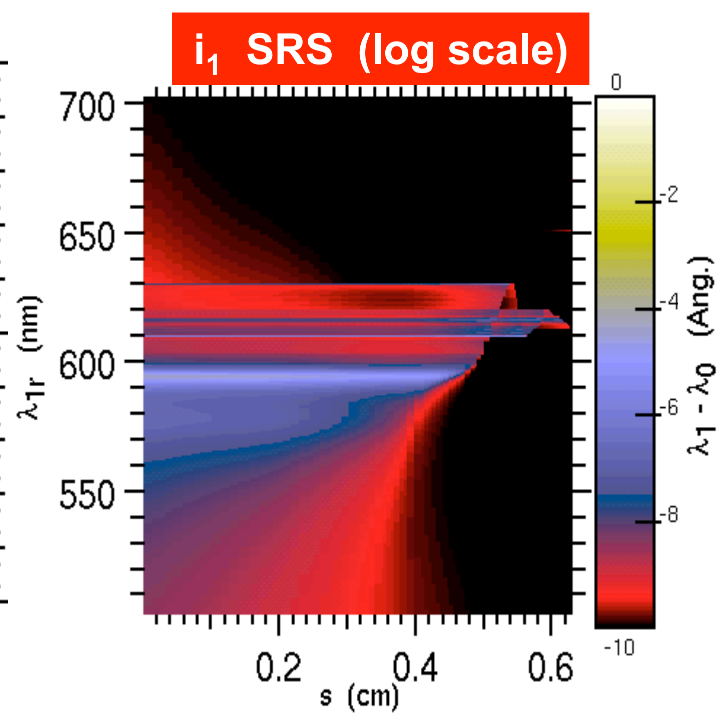


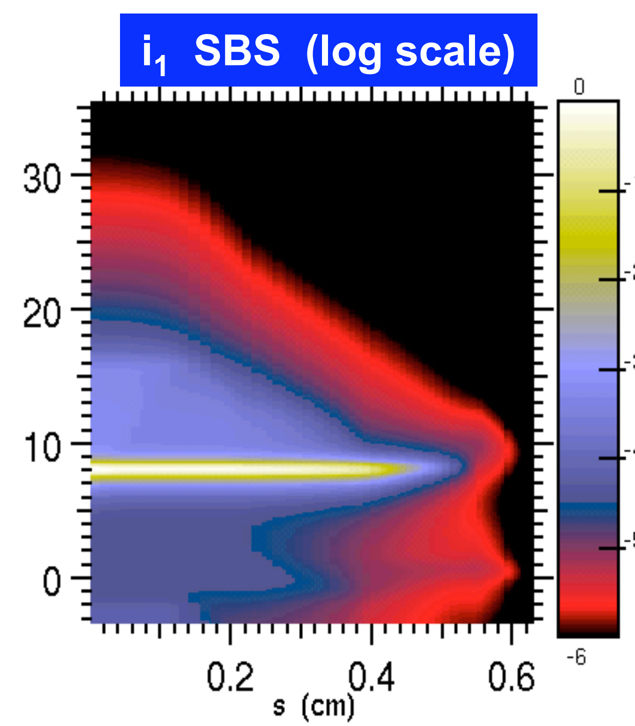

# DEPLETE and NEWLIP gain have similar reflected-light spectra

270V Be

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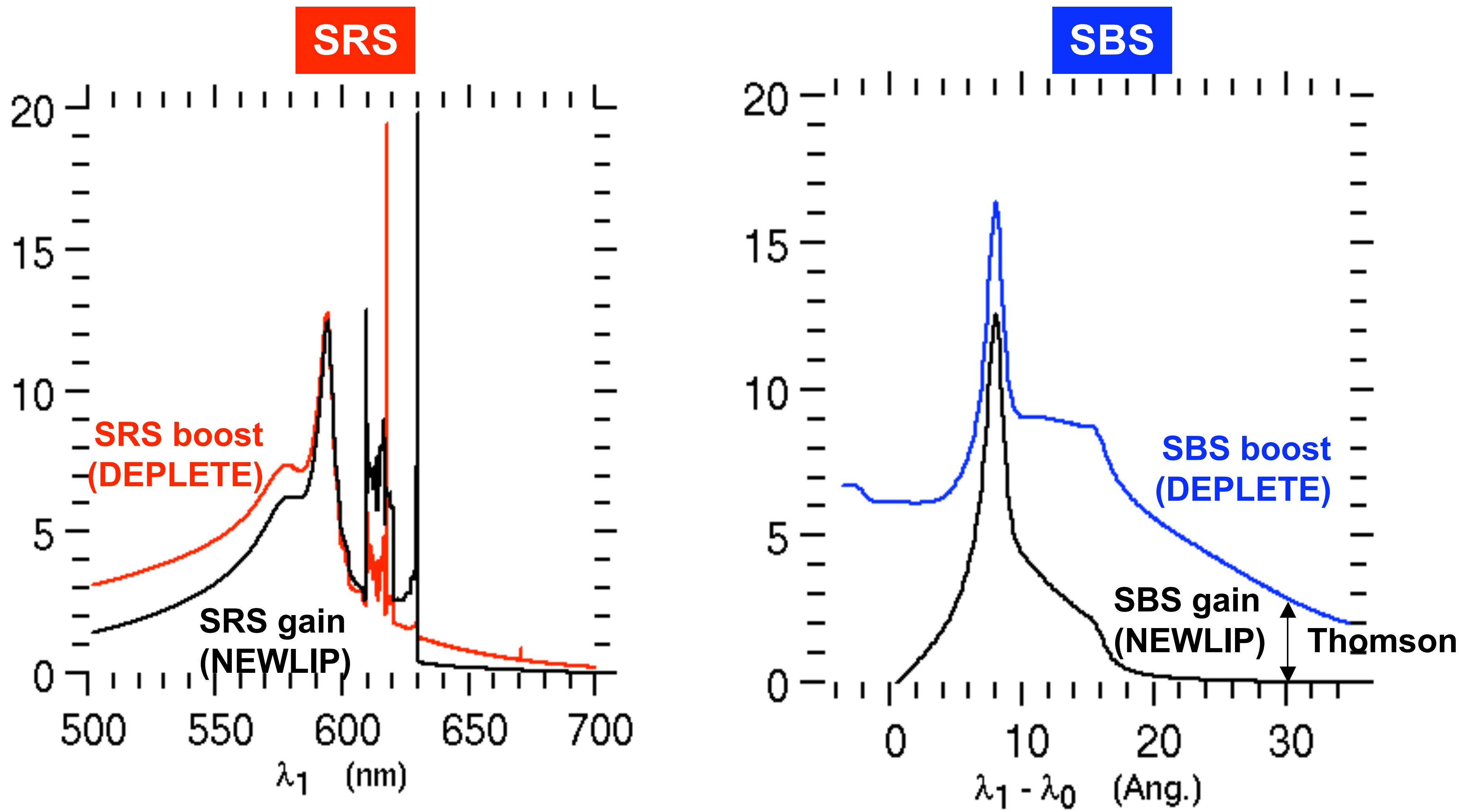
$$\text{DEPLETE ``Boost''} = \log\left[\frac{\text{scattered spectrum with brem., Thomson, and coupling}}{\text{scattered spectrum with just bremsstrahlung (i.e. no laser)}}\right] = \frac{\text{``backscatter''}}{\text{``noise''}}$$



# DEPLETE and pF3D patch agree pretty well (on a log scale); speckle effects may enhance SRS

270V Be

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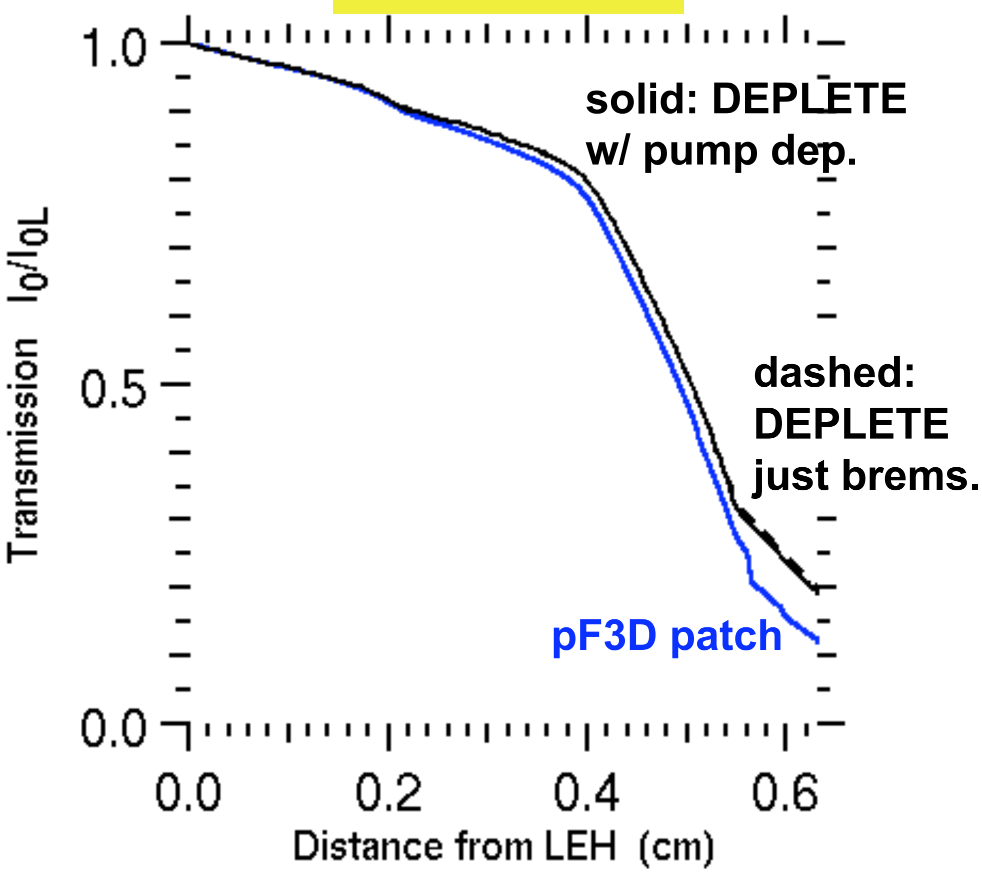
**pF3D patch: "ray with speckles:" 3D, whole ray path, a few speckles in transverse directions.**

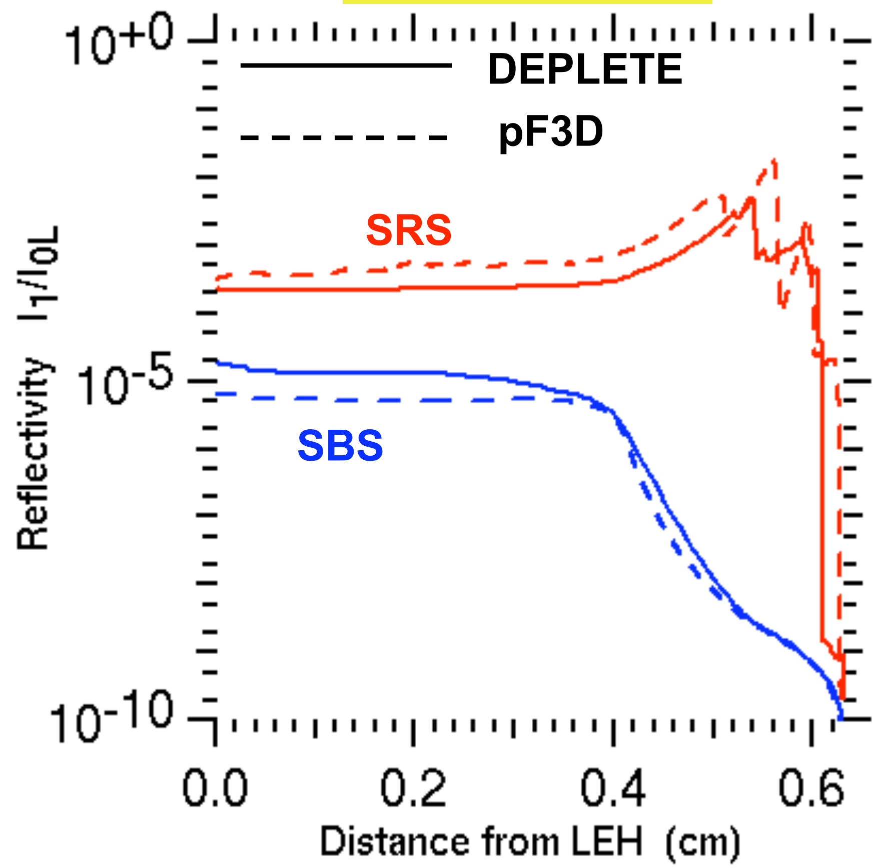
**pF3D has more SRS: probably due to higher gain in high-intensity speckles.**
**pF3D has less SBS: probably due to more pump depletion.**

**The decent agreement of DEPLETE and pF3D scattered intensities validates DEPLETE's 1-D model of 3-D noise.**

**Transmission**




**Reflected light**



# The plasma-wave amplitude predicted by DEPLETE can be compared with nonlinearity thresholds

270V Be

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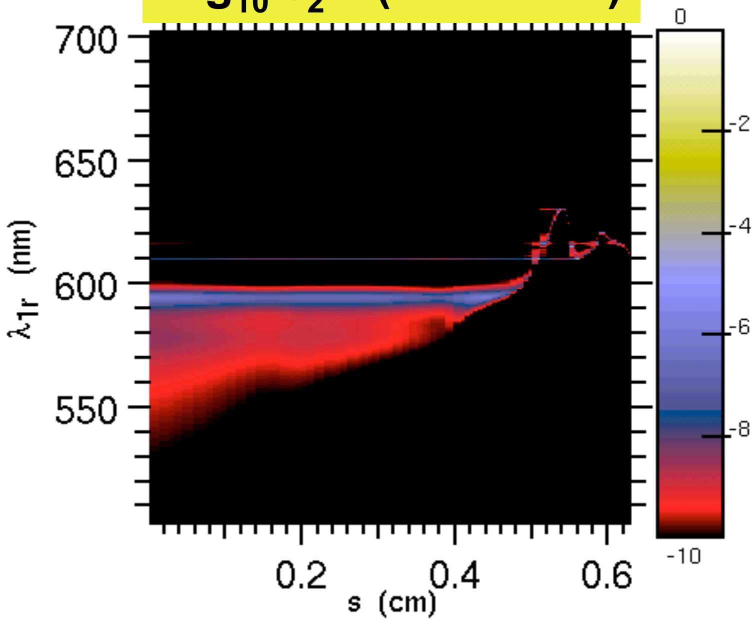
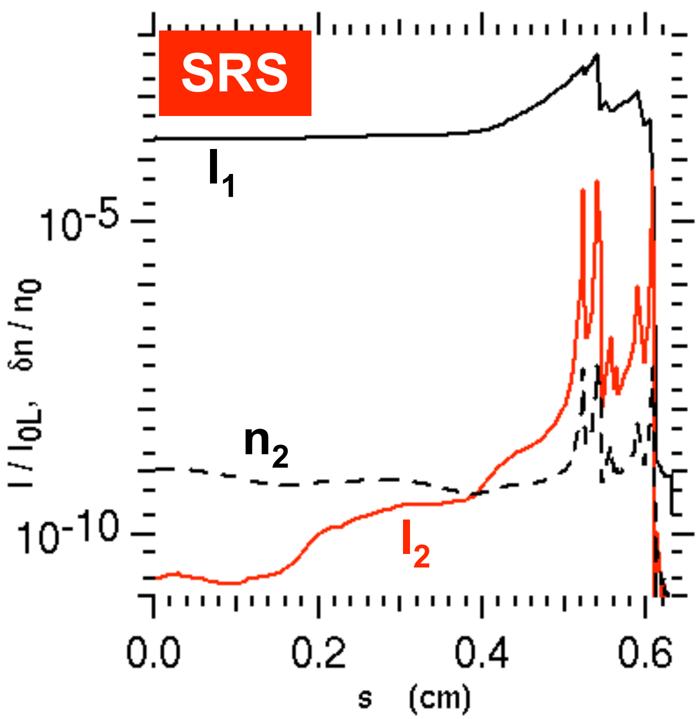
**$\log_{10} \delta_2$ (arb. units)**

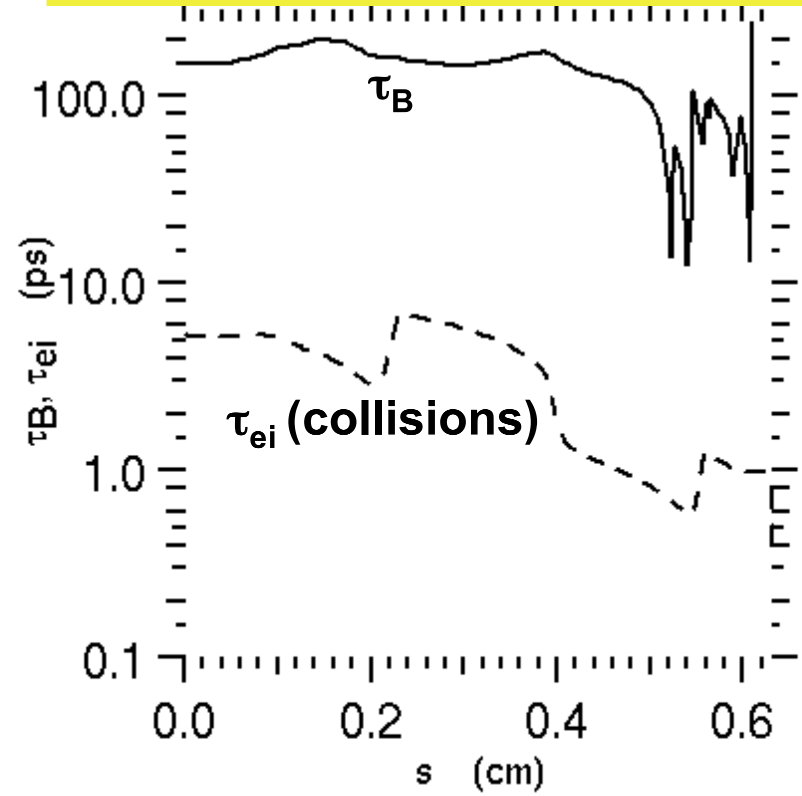



$$\frac{n_2}{n_e} = \frac{1}{2}\left|\frac{\chi_e}{\epsilon}\right|(k_2\lambda_{De})^2\frac{v_{os,0}v_{os,1}}{v_{Te}^2}$$

$$\frac{n_2}{n_{e0}} = \left[\int d\omega_1\ \delta_2\right]^{1/2} \qquad \tau_B\omega_{pe} = 2\pi\left[\frac{n_{e0}}{n_2}\right]^{1/2}$$

**SRS electron plasma wave: too weak for trapping nonlinearities**



# Conclusions and Future Prospects



**Conclusions:**

- DEPLETE provides a 1-D, steady-state, ray-based, linear kinetic calculation of backscatter:
  - Pump depletion, re-absorption, 1-D physical noise included.
- Compares well with NEWLIP gains.
- pF3D comparisons are promising; need to include speckle effects in DEPLETE for better agreement.

**Future prospects:**

- DEPLETE can be incorporated into rad-hydro codes:
  - ray-based (just like rad-hydro) and computationally fast (~secs. per ray).
  - An effective absorption coefficient, calculated from the DEPLETE solution (including scattered and plasma wave intensities) can replace the bremsstrahlung damping rate in the rad-hydro code.
- DEPLETE gives plasma wave intensities, which can be compared to nonlinearity thresholds (Langmuir decay instability, trapping, kinetic inflation, Langmuir wave self-focusing).
- Hot electron production can be estimated as well.
- DEPLETE can indicate regions where kinetic simulations may be especially illuminating.