Interplay of Trapping and Density Gradients in Raman Scattering

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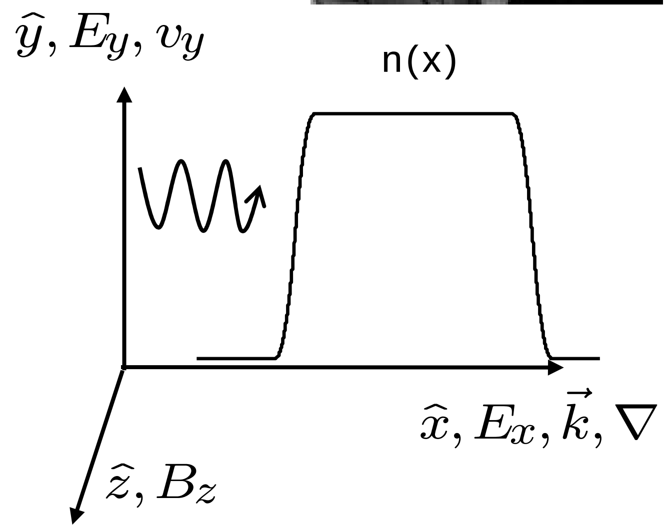
Raman Scattering in large $k_2\lambda_{De}$ plasmas

- Experiments[1] and simulations[2] show larger Raman reflectivity than linear convective gain estimates, even though Landau damping is large.
- Electron trapping reduces the Landau damping of the plasma wave and enhances Raman; it also shifts the plasma wave frequency and limits bursts of Raman.
- Inhomogeneity introduces a wavenumber mismatch and also limits Raman, even for undamped daughter waves[3].
- Study Raman scattering when trapping and inhomogeneity are important, via kinetic simulations.

[1] J. C. Fernández, J. A. Cobble, et al. *Phys Plasmas* **7**, 3743 (2000).
[2] H. X. Vu, D. F. DuBois, B. Bezzerides. *Phys Plasmas* **9**, 1745 (2002).
[3] M. N. Rosenbluth, *PRL* **29** (1972).

ELVIS: EuLerian Vlasov Integrator w/ Splines
1D Vlasov-Maxwell Code

[D. J. Strozzi, M. M. Shoucri, A. Bers, *Comp Phys Comm* (2004, in press)]



- Vlasov (kinetic, collisionless) Equation in x:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} - e(E_x + v_y B_z)\frac{\partial f}{\partial p} = 0$$

- Gauss' Law: $\partial_x E_x = e\epsilon_0^{-1}(Z_i n_i - n_e)$

- Transverse Maxwell Fields: fixed, linearly polarized in $\hat{y}$

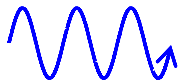
$E^{\pm} \equiv E_y \pm cB_z \qquad (\partial_t \pm c\partial_x)E^{\pm} = -\epsilon_0^{-1} J_y \qquad E^{\pm} =$ right,left-moving

- Transverse flow: cold collisionless fluid

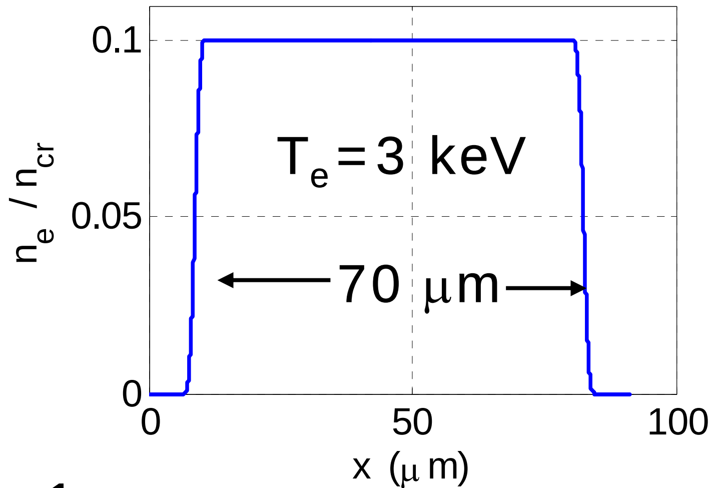
$$m\partial_t v_y = -eE_y$$

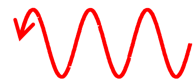
Homogeneous plasma: Raman far exceeds convective gain for $t > \tau_B$ (no sideloss)

$I_0 = 2\times10^{15}$ W/cm^2
$\lambda_0 = 351$ nm



n_e at $t=0$





$I_1 = 10^{10}$ W/cm^2
$\lambda_1 = 574$ nm

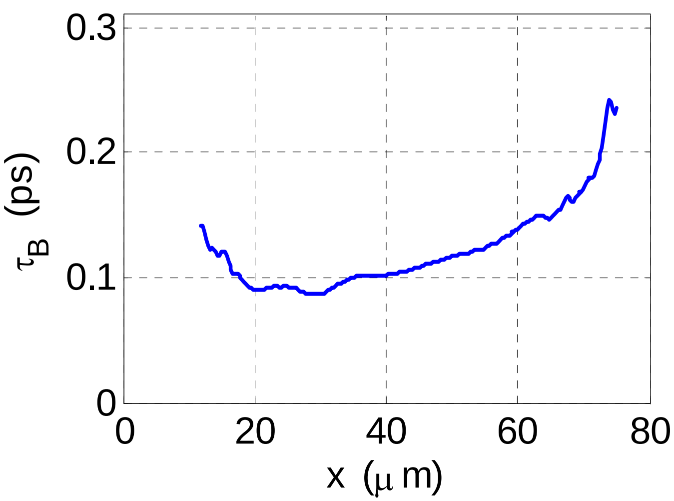
$k_2\lambda_{De} = 0.36$
$\nu_2 = 0.032\ \omega_2$

0: pump e/m wave
1: back e/m wave
2: plasma wave

convective gain:

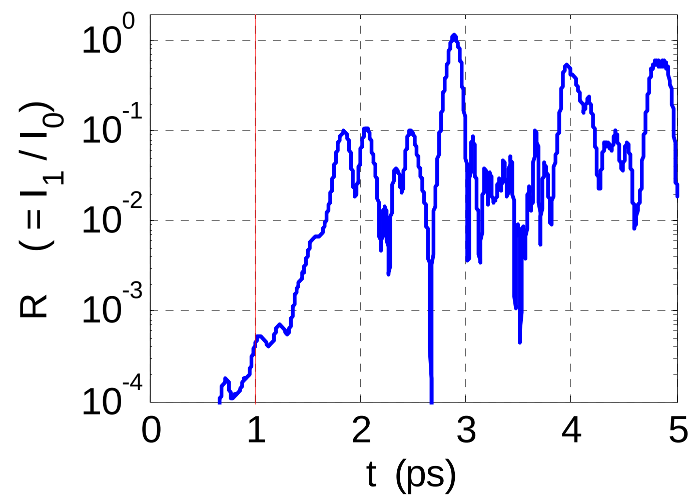
$R = 6.1\times10^{-5}$

bounce time at t=1 ps



$$\omega_B = \sqrt{\frac{eE_xk}{m_e}} \qquad \tau_B = \frac{2\pi}{\omega_B}$$

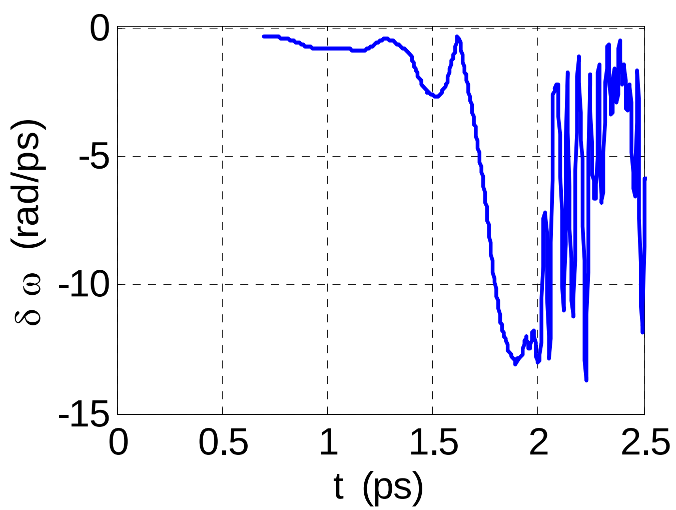
Reflectivity <R>=12%



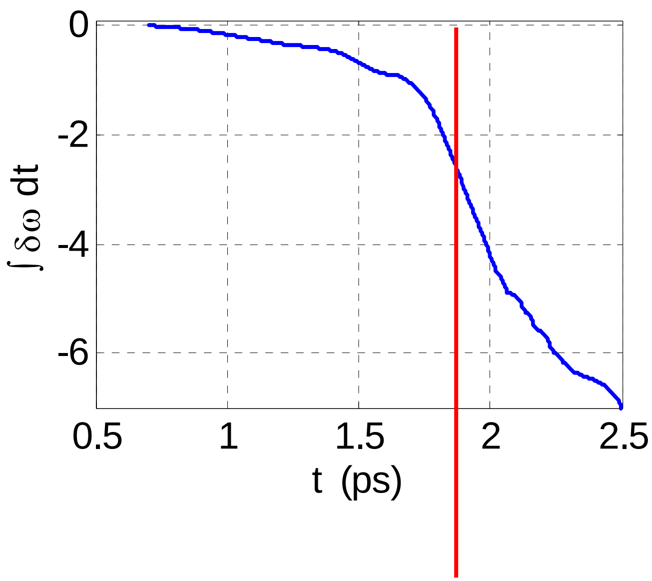
Landau damping reduced for $t \gtrsim \tau_B$
[T. O'Neil, *Phys. Fluids* **8** (1965)]

Phase due to frequency shift ≈ 3 at First Peak

Frequency shift at box center



$\int \delta\omega_2$ dt =Phase from freq shift at box center



First Raman peak

$$\delta\omega_2(t \gg \tau_B) = \sqrt{\frac{e\phi_2}{T_e}} h(v_{p2}/v_{te}) < 0$$

[G. J. Morales and T. M. O'Neil. *PRL* **28**, 417 (1972)]

∇ n: damping controls width of gain region

$$
\begin{aligned}
n(x) &= n_0(1 + x/L_n) \\
\kappa' &= \frac{d}{dx}(k_0 - k_1 - k_2) \approx \frac{1}{6 L_n \lambda_{De}^2 k_2} \\
G &= 2\pi \frac{\gamma_0^2}{|v_{g1} v_{g2} \kappa'|} \sim I_0 |L_n| \qquad \text{intensity gain exponent}
\end{aligned}
$$

0: pump e/m wave
1: back e/m wave
2: plasma wave

Three–wave model

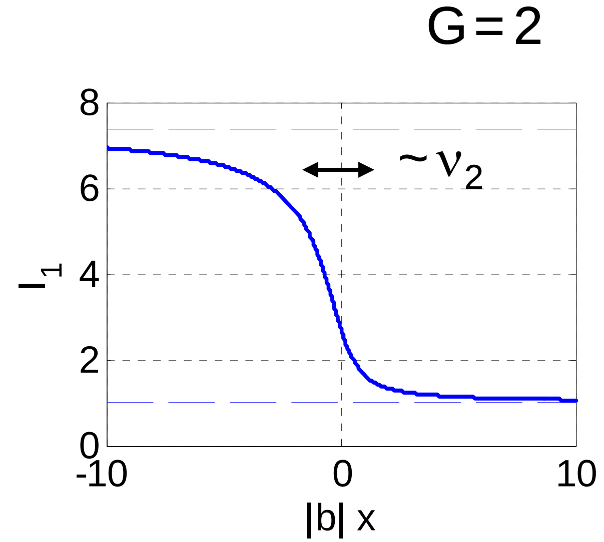
$$\tilde{a}_2 = a_2 \exp\left[-\frac{i}{2}\kappa' x^2\right]$$

$$
\begin{aligned}
(\partial_t + v_{g1}\partial_x) a_1 &= \gamma_0 \tilde{a}_2^* \\
(\partial_t + v_{g2}\partial_x + \nu_2 + i\kappa' v_{g2} x)\tilde{a}_2 &= \gamma_0 a_1^*
\end{aligned}
$$

Strong damping limit steady state: $\nu_2 \, a_2 \gg v_{g2}\partial_x \, a_2$

$$I_1 = |a_1|^2 \qquad b = \frac{v_{g2}\kappa'}{\nu_2}$$

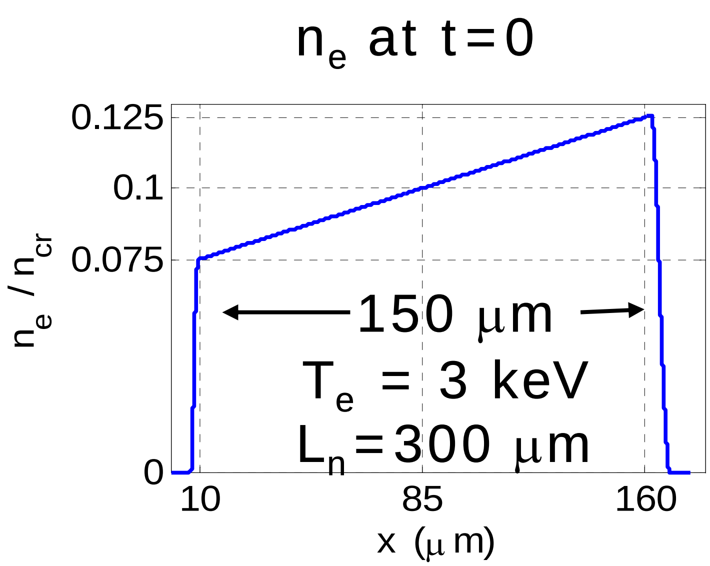
$$
\begin{aligned}
I_1(x) &= I_{10} \exp\left[(G/\pi)(\arctan|b|x_0 - \arctan|b|x)\right] \\
&\to I_{10} \exp G \qquad\qquad \nu_2 \to 0
\end{aligned}
$$



Same gain over x=±∞ as ν_2=0 analysis

[M. N. Rosenbluth, *PRL* **29** (1972)]

Predicted Reflectivity in Steady State

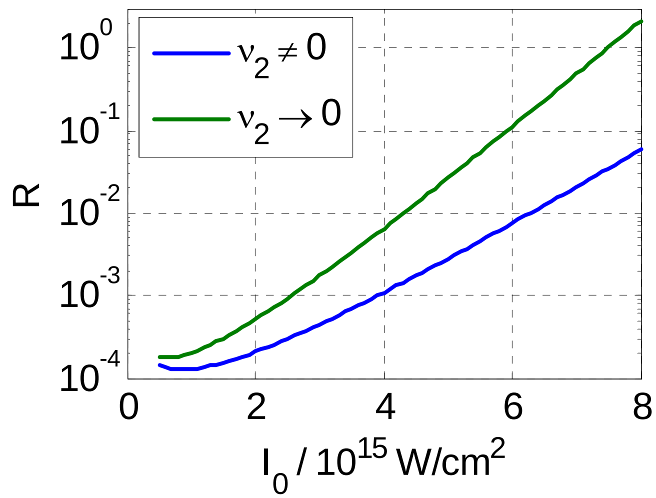


seed: $I_1 = 4 \cdot 10^{10}$ W/cm^2

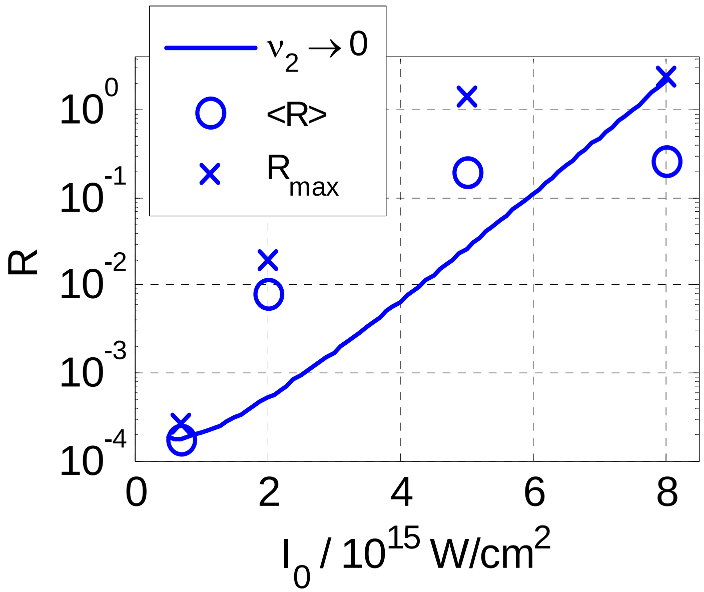
$\lambda_{1,vac}$=570 nm

$$R = \frac{I_{1,seed}}{I_0} \exp\left[G\frac{1}{\pi}(\arctan|b|x_r - \arctan|b|x_l)\right]$$

$$\rightarrow \frac{I_{1,seed}}{I_0} e^G \qquad \nu_2 \rightarrow 0 \qquad b = \frac{v_{g2}\kappa'}{\nu_2}$$



Pump from low-n side: Freq Shift fights ∇ n



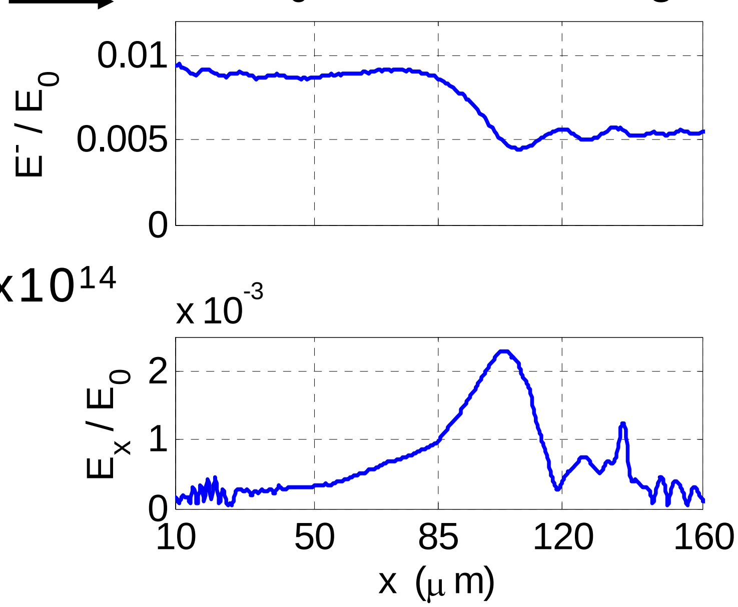
$$\text{phase mismatch: } \psi = \int \kappa dx - \int \Delta\omega dt$$
$$\approx \tfrac{1}{2}\kappa' x^2 - \int |\delta\omega_2| dt$$
$$\delta\omega_2(t \gg \tau_B) = \sqrt{\frac{e\phi_2}{T_e}}\, h(v_{p2}/v_{te}) < 0$$
$$\text{sign } \kappa' = \text{sign } L_n > 0$$

∴ κ' and $\delta\omega_2$ counteract each other

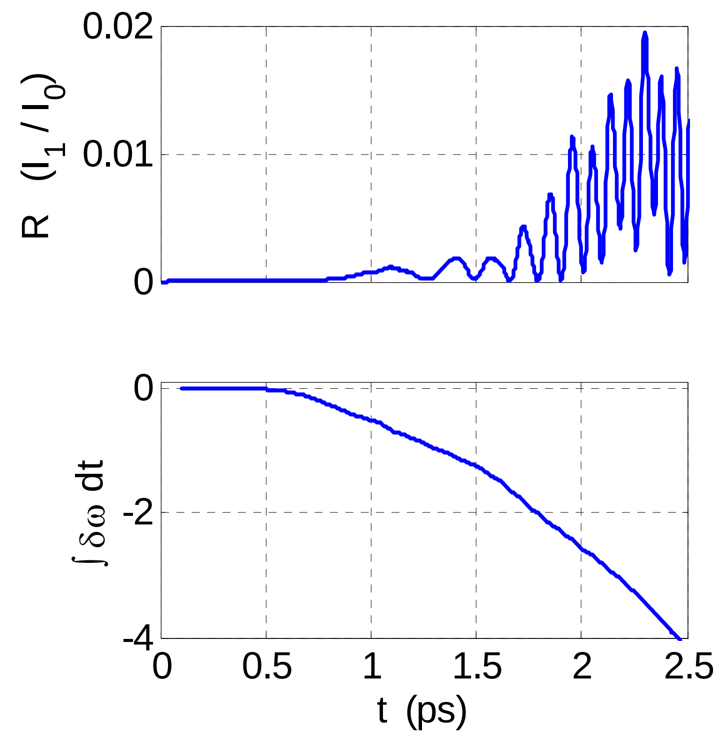
Plasma wave grows along pump k
(lower linear Landau damping)

pump ⟶ low n_e high n_e

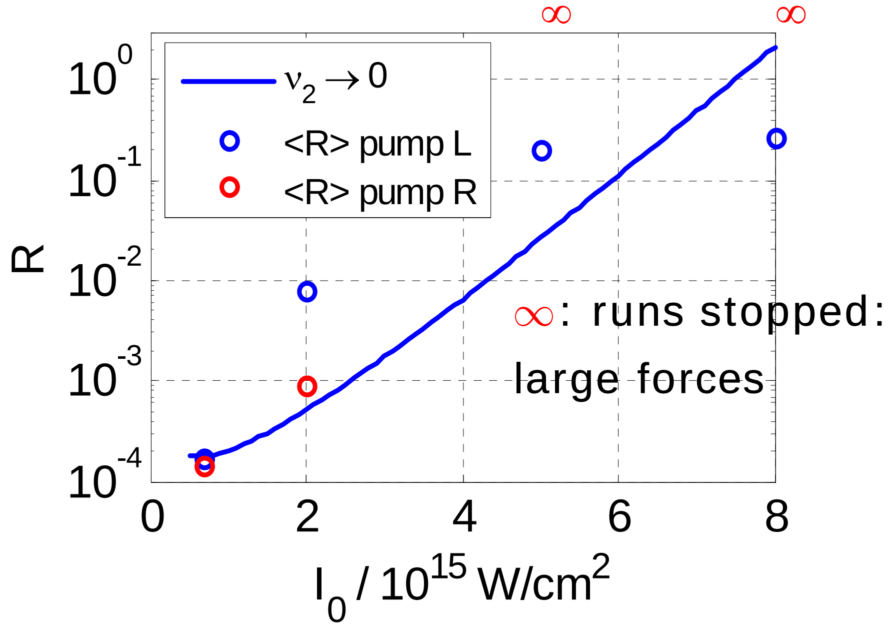
$I_0 = 7\text{x}10^{14}$

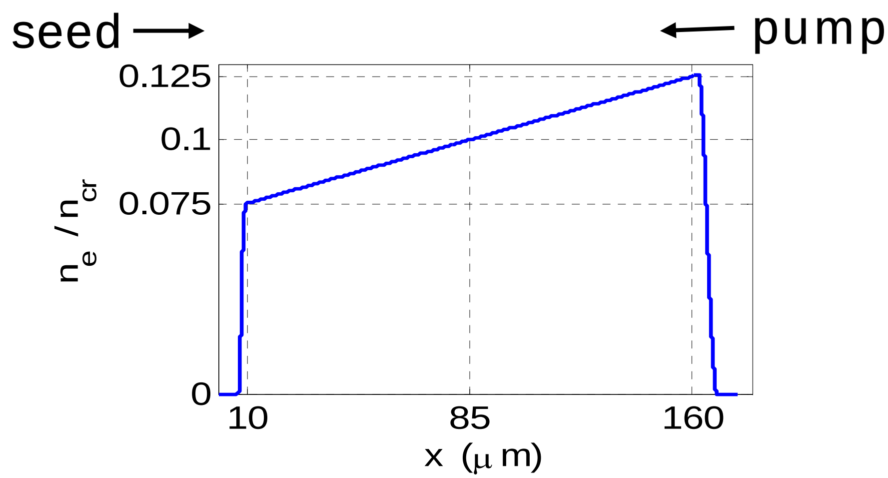


$I_0 = 2\text{x}10^{15}$



Pump incident on high-n_e side

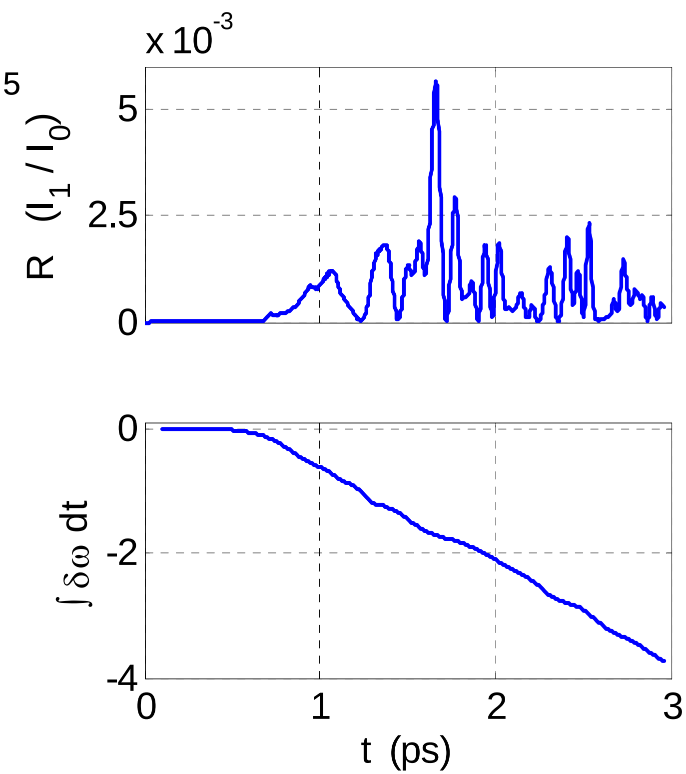




$$\psi = \tfrac{1}{2}\kappa' x^2 - \int |\delta\omega_2| dt$$

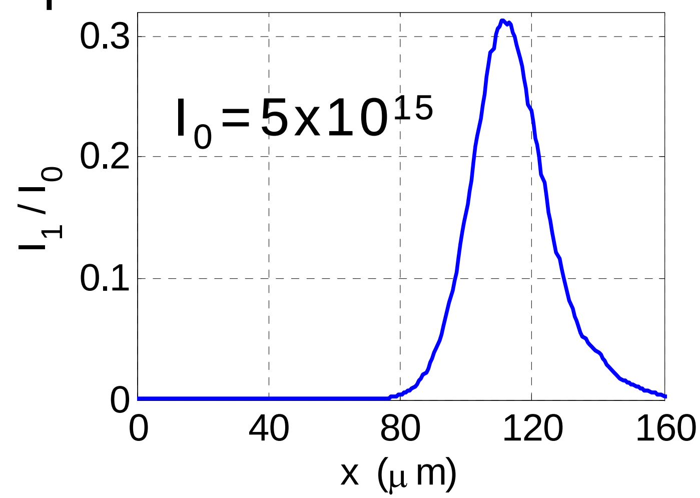
$$\text{sign } \kappa' = \text{sign } L_n < 0$$

$I_0 = 2\text{x}10^{15}$



$\therefore$ κ' and $\delta\omega_2$ cooperate

t=0.75 ps



Summary and Future Work

Summary: In a high-$k_2\lambda_{De}$, inhomogeneous plasma

- Weak Pump: linear gain is seen.

- Moderate Pump: Frequency shift can enhance Raman if it counteracts dephasing due to inhomogeneity.

- High Pump: Spatial variation of Landau damping enhances Raman from the high-density region, especially when scattered light grows into it.

Future work:

- **Sideloss** out of laser speckle or beam detraps electrons. What effect does this have? ELVIS has a Krook operator to address this.

- Are **ions** relevant? Does the Langmuir Decay Instability of the plasma wave saturate Raman? ELVIS has option for mobile ions.

- **Steepen profile** on high-n side to reduce Raman from low-damping region.