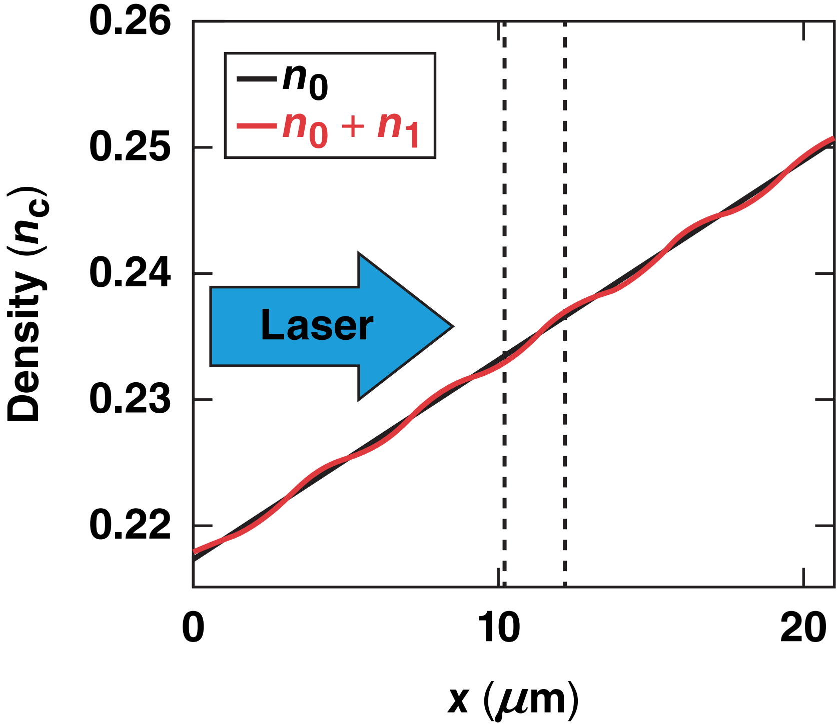
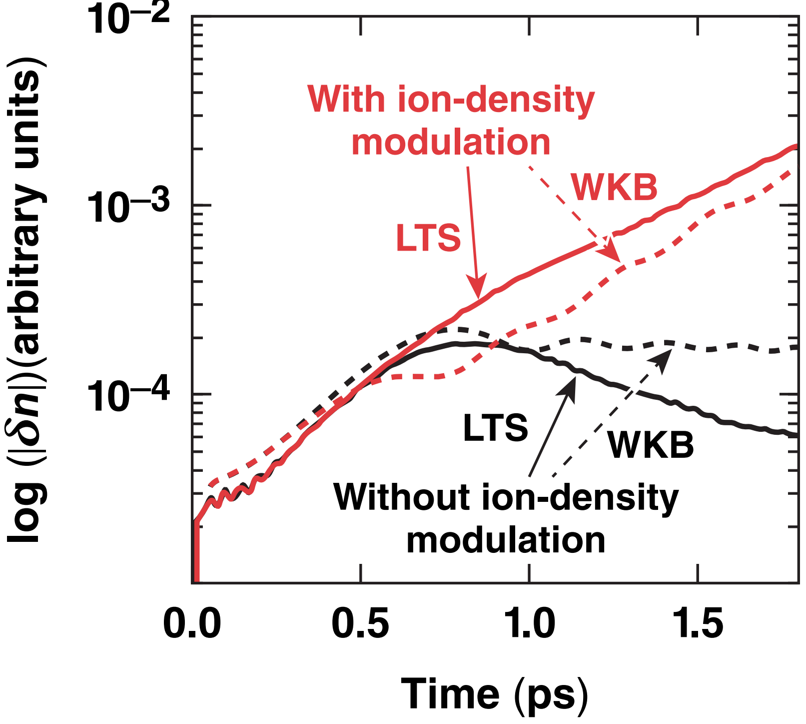
Density-Modulation–Induced Absolute Laser–Plasma Instabilities: Simulations and Theory

Sinusodial n_1



Plasma-wave amplitude (δn_e) in LTS and WKB simulations



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Summary

Fluid simulations show that a static ion-density modulation can change the convective unstable modes away from the quarter critical surface to absolute modes

- This conversion can occur for two-plasmon–decay (TPD) and stimulated Raman scattering (SRS) instabilities under realistic direct-drive inertial confinement fusion (ICF)conditions
- A sufficiently large change of the density gradient in a linear density profile can change the convective unstable modes to absolute modes
- An analytical expression is derived for the threshold of the gradient change, which depends only on the convective gain

Collaborators

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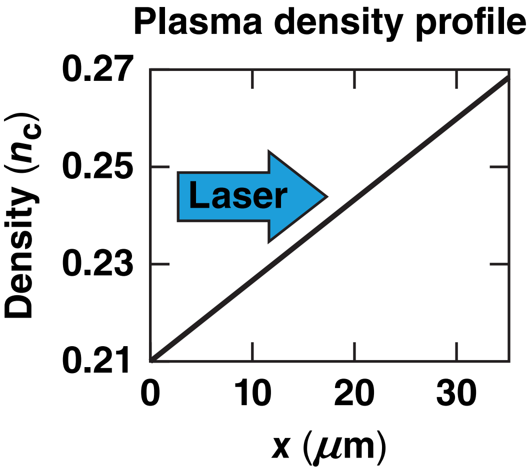
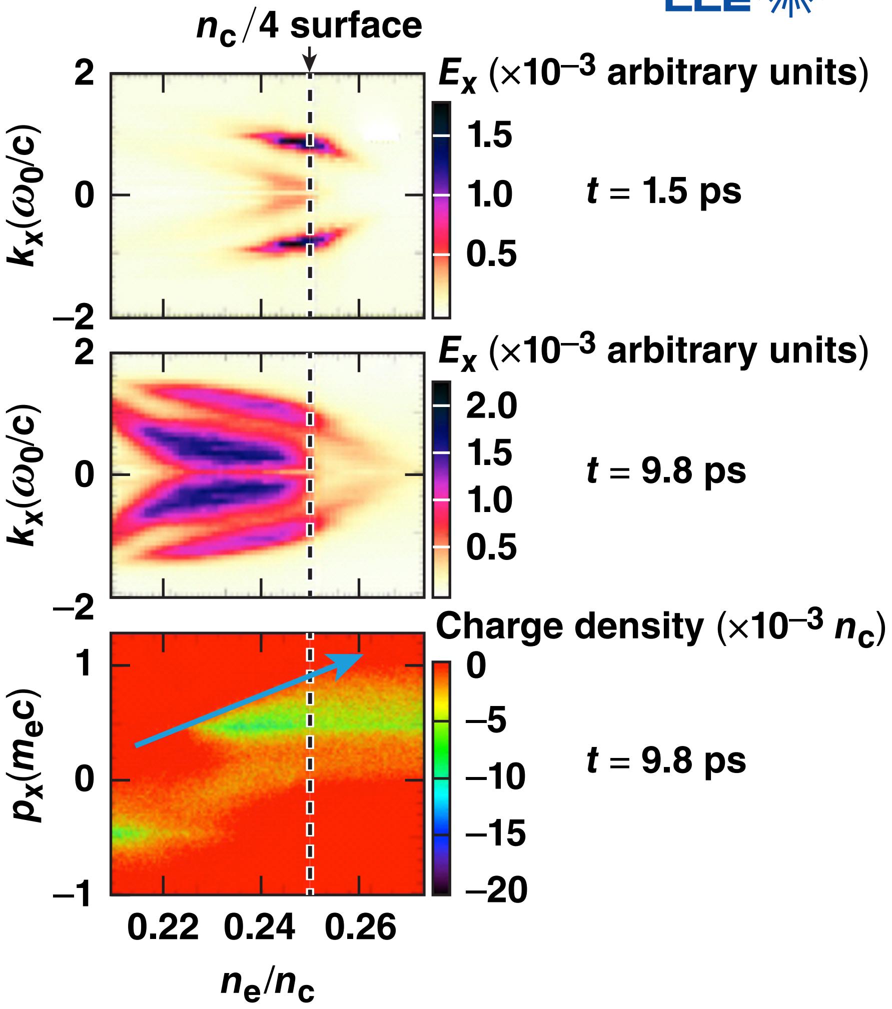
Laboratory for Laser Energetics

Motivation

Our previous study* found that the TPD instability in a plasma with ion-density fluctuation plays an important role in hot-electron generation

L = 150 nm
T_e = 3 keV
$I = 6 \times 10^{14}$ W/cm^2





- TPD modes away from the $n_c/4$ surface appear in the nonlinear stage and form the first stage of electron acceleration
- These modes were linked to ion-density fluctuations

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*R. Yan *et al.*, Phys. Rev. Lett. 108, 175002 (2012).

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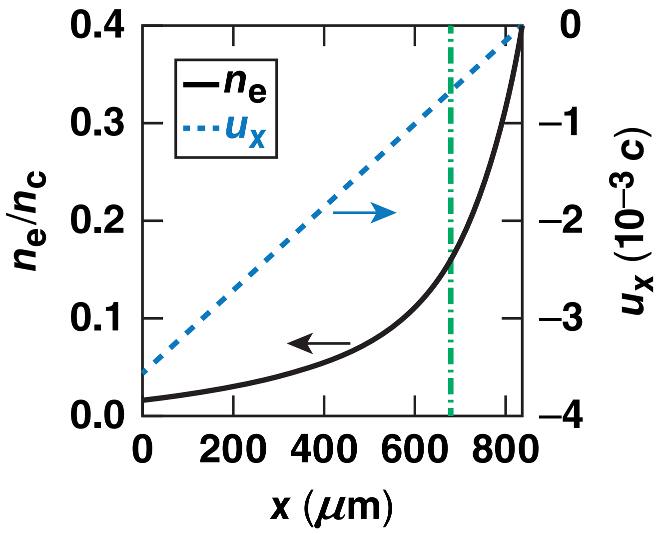
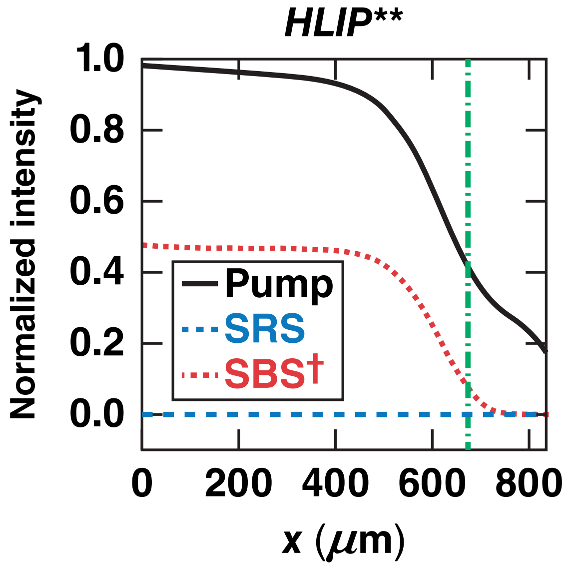
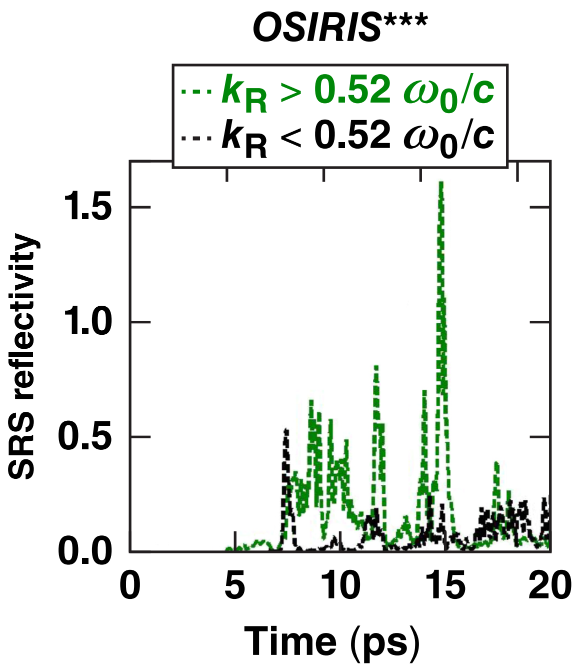
Motivation

The particle-in-cell (PIC) simulation had a higher SRS reflectivity than a fluid code that considers only the convective gains with shock-ignition parameters*



L = 170 μm
T_e = 1.6 keV
$I = 5 \times 10^{15}$ W/cm^2





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*L. Hao *et al*., Phys. Plasmas 23, 042702 (2016).

**L. Hao *et al*., Phys. Plasmas 21, 072705 (2014).

***R. Fonseca *et al*., Lect. Notes Comput. Sci. 2331, 342 (2002).

†SBS: stimulated Brillouin scattering

Ion-density modulation can change the convective unstable modes to absolute modes

- A previous study found that 1-D convective SRS modes can become absolute in the presence of ion-density modulation
  - the growth rates of the absolute modes reach a maximum at certain ion-density modulation amplitudes and wavelengths*
  - the absolute thresholds for parabolic and sinusoidal density profiles and the growth rates for the parabolic density profile were derived theoretically with WKB solutions**
- We study the behavior of TPD instability under ion-density fluctuations using *LTS* and WKB-type fluid simulations for direct-drive ICF
- *LTS* solves the linear TPD equations with arbitrary density profiles
  - the TPD growth rates under linear density profiles were benchmarked with theory***

$$\frac{\partial \psi}{\partial t} = \phi - 3\nu_e^2 \frac{n_p}{n} - \vec{\nu}_0 \cdot \nabla \psi$$

$$\frac{\partial n_p}{\partial t} = -\nabla \cdot (n \nabla \psi) - \vec{\nu}_0 \cdot \nabla n_p$$

$$\nabla^2 \phi = n_p$$

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*D. R. Nicholson and A. N. Kaufman, Phys. Rev. Lett. 33, 1207 (1974);
D. R. Nicholson, Phys. Fluids 19, 889 (1976).

**G. Picard and T. W. Johnston, Phys. Fluids 28, 859 (1985);
E. A. Williams and T. W. Johnston, Phys. Fluids B 1, 188 (1989).

***R. Yan, A. V. Maximov, and C. Ren, Phys. Plasmas 17, 052701 (2010).

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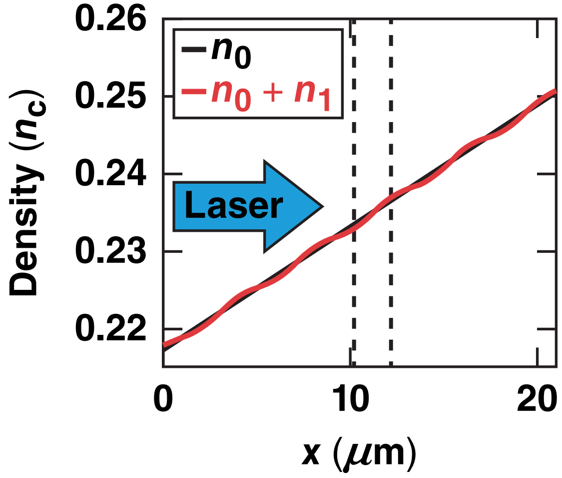
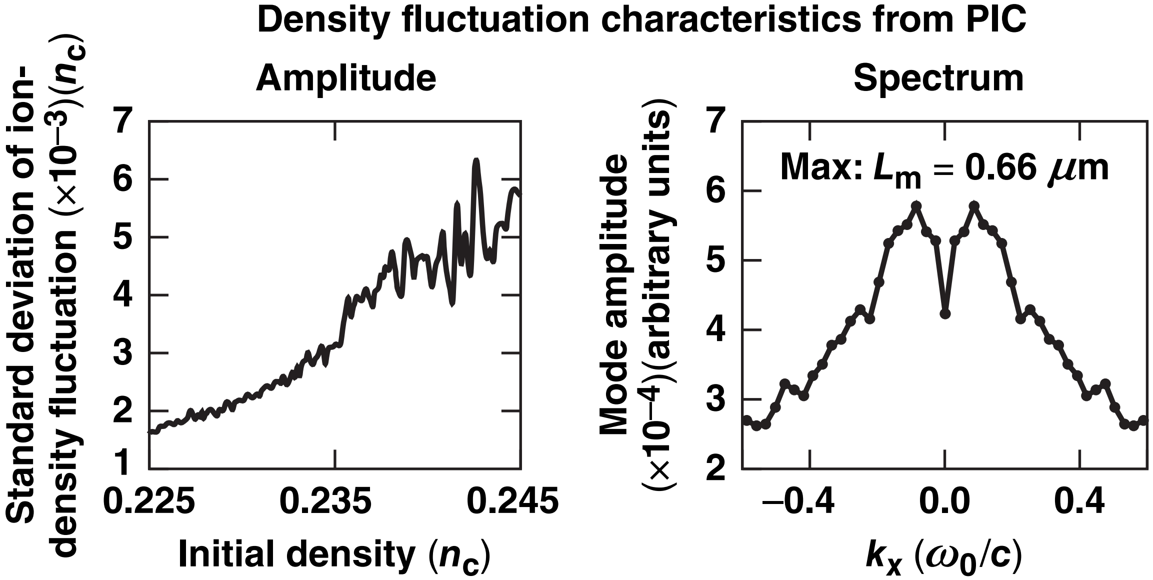
We study TPD modes with sinusoidal static ion-density modulation in 2-D *LTS** simulations

L = 150 nm
T_e = 3 keV
$I = 6 \times 10^{14}$ W/cm^2

Sinusodial n_1



Density fluctuation characteristics from PIC



- A static density modulation $n_1 = \Delta n \sin(x/L_m)$ is added to a linear density profile n_0 with the amplitude and wavelength relevant to *OSIRIS* simulation results

$$\Delta n = 0 \text{ to } 3 \times 10^{-3}\, n_c$$

$$L_m = 0.1 \text{ to } 1.7\ \mu\text{m}$$

- The amplitudes of the TPD modes inside a narrow region centered at 0.235 n_c are measured to determine the existence of absolute modes

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*R. Yan, A. V. Maximov, and C. Ren, Phys. Plasmas 17, 052701 (2010).

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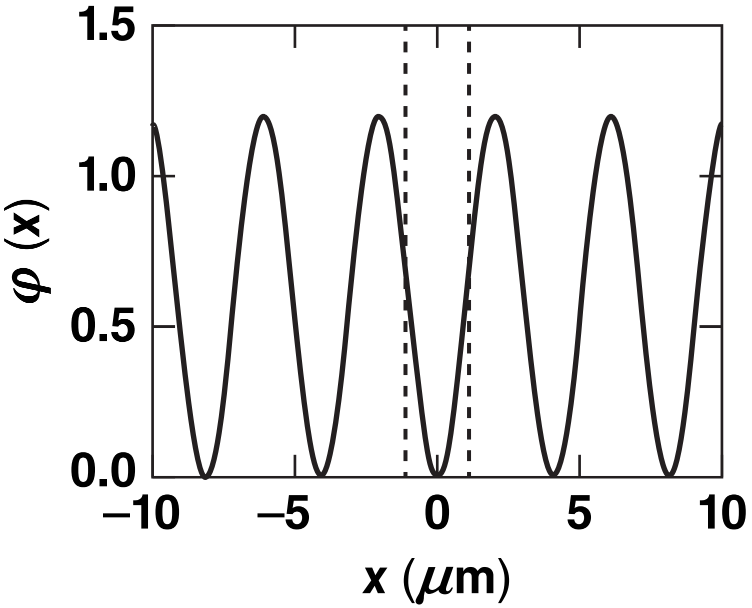
To isolate the essential physics, we also study the TPD modes in 1-D WKB-type simulations

Phase mismatch caused by ion-density modulations



L = 150 μm
T_e = 3 keV
$I = 6 \times 10^{14}$ W/cm^2

- Our WKB code solves these equations

$$\left(\frac{\partial}{\partial t} + V_1 \frac{\partial}{\partial x}\right) a_1 = \gamma_0 a_2 e^{i\frac{\kappa'}{2}x^2 + i\varphi(x)}$$

$$\left(\frac{\partial}{\partial t} + V_2 \frac{\partial}{\partial x}\right) a_2 = \gamma_0 a_1 e^{-i\frac{\kappa'}{2}x^2 - i\varphi(x)}$$

$$\Delta k = k_m \sin \frac{x}{L_m}$$

$$\varphi(x) = \int_0^x \Delta k dx = k_m L_m \left(1 - \cos \frac{x}{L_m}\right)$$

- The typical amplitude of phase mismatch is $k_m L_m = 0.6$ for

$$\Delta n = 6 \times 10^{-4}\, n_c,\ L_m = 0.65\ \mu\text{m}$$

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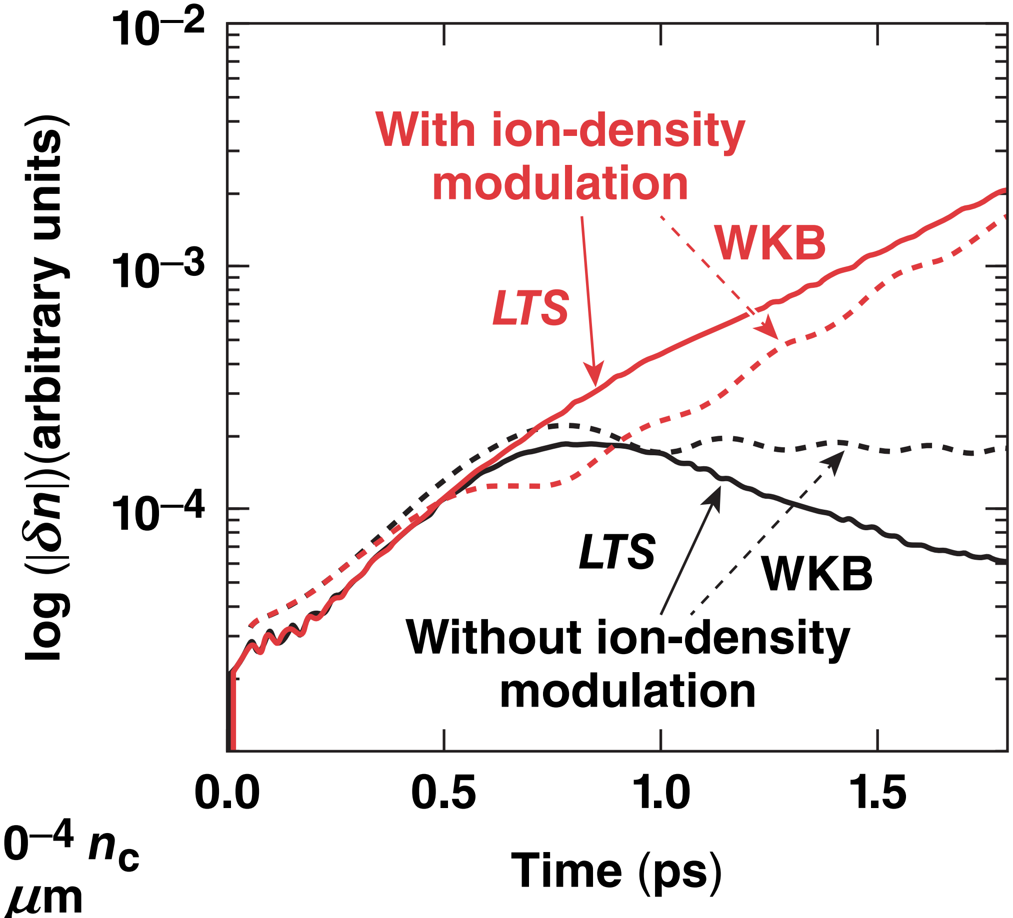
LTS and WKB simulations reasonably agree

Plasma-wave amplitude (δn_e) in *LTS* and WKB simulations



$\Delta n = 6 \times 10^{-4}\, n_c$

$L_m = 0.65\ \mu m$

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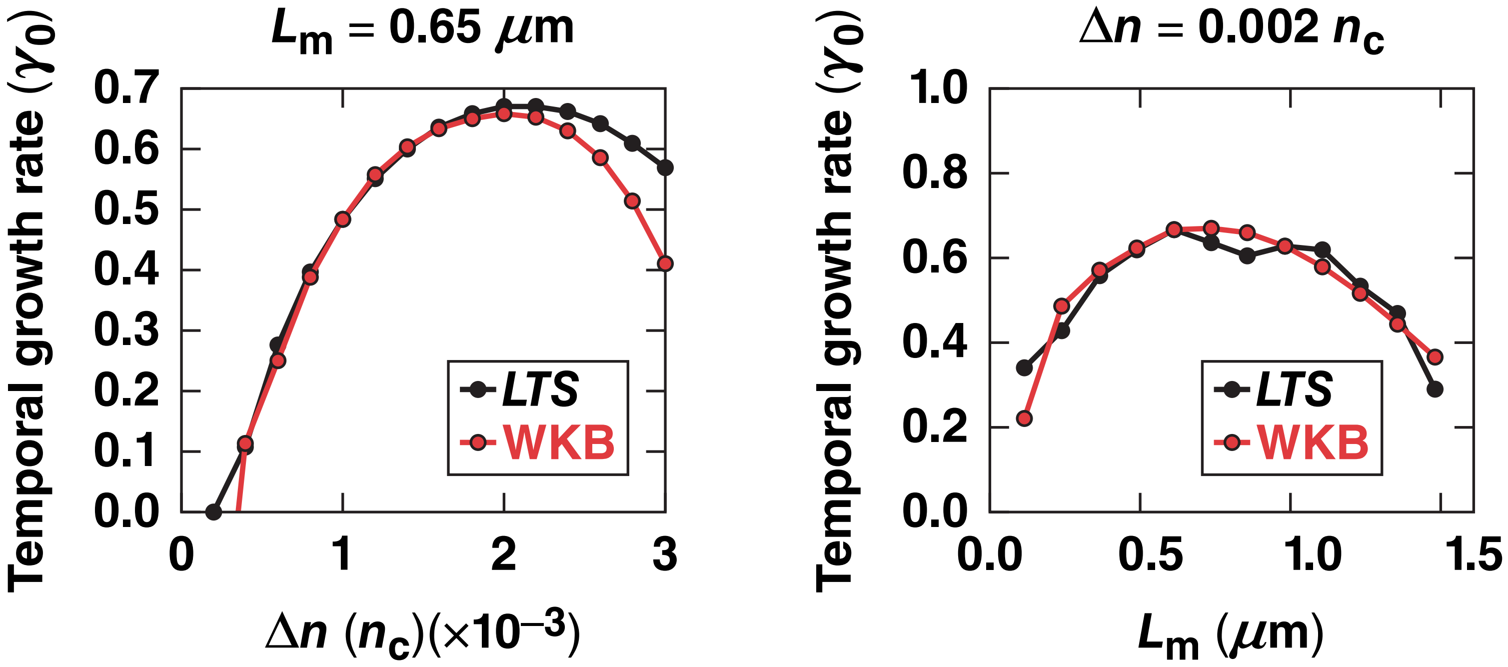
The maximum absolute growth rate is ~70% of the corresponding homogeneous TPD growth rate γ_0



Typical density fluctuation in the PIC simulations: $\Delta n = 0$ to $3 \times 10^{-3}\ n_c$

$L_m = 0.1$ to $1.7\ \mu m$

- The growth rate is 4× of that of the absolute modes near the $n_c/4$ region

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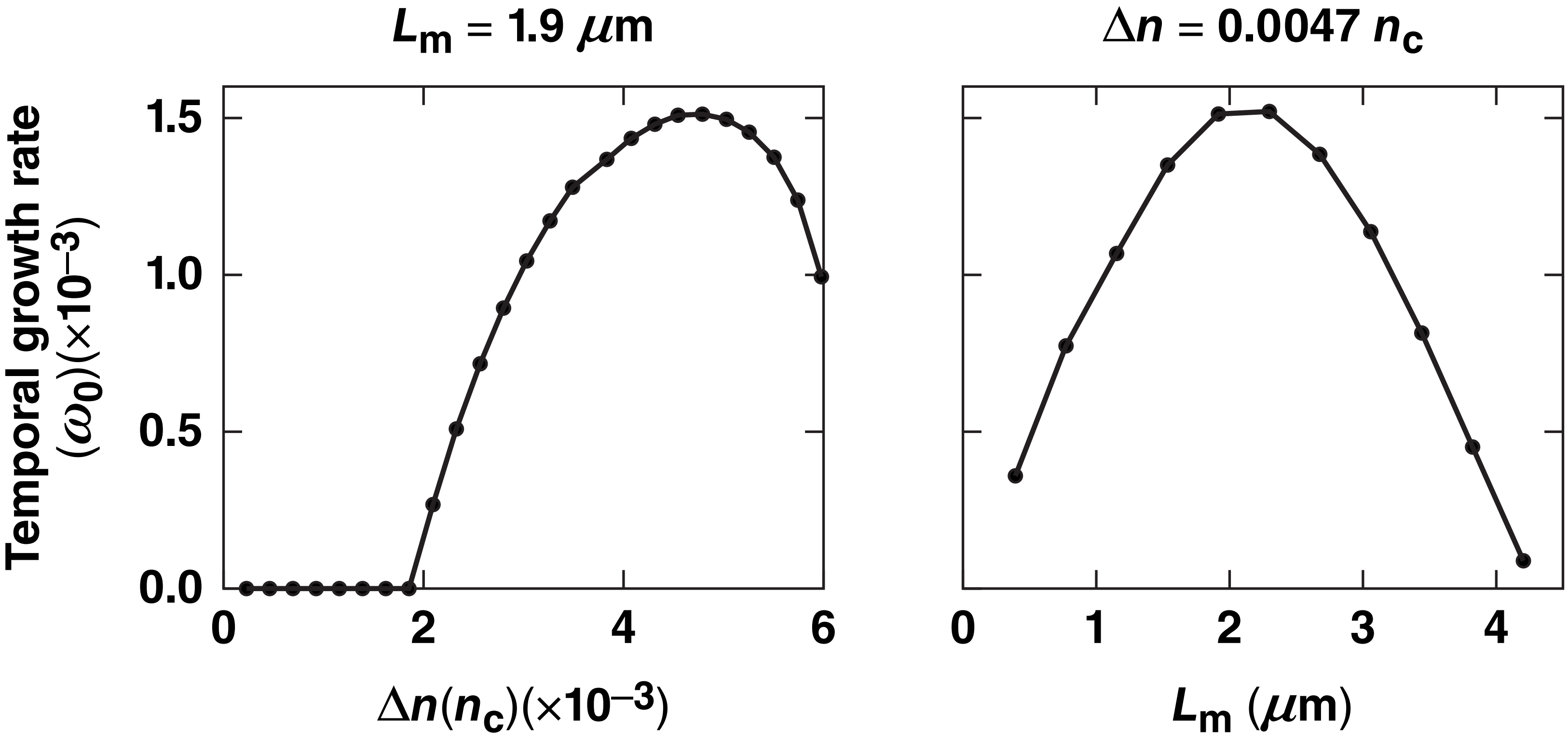
This convective-to-absolute conversion also occurs for SRS instability under shock-ignition conditions



SRS $I = 2 \times 10^{15}$ W/cm^2, $n_e = 0.22\ n_c$, $L = 150\ \mu m$

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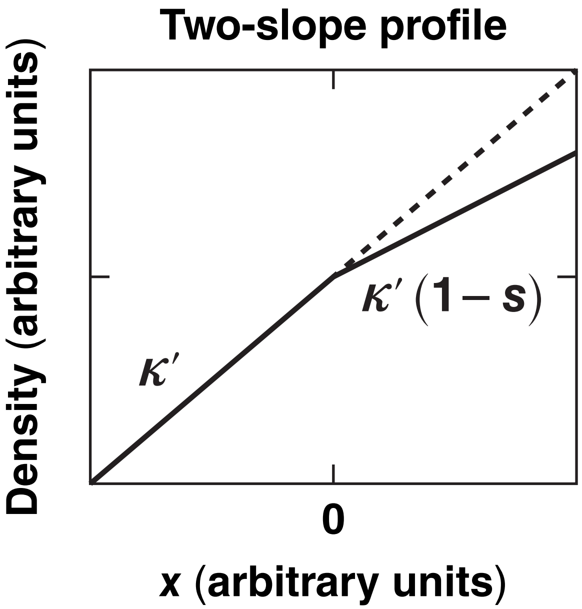
A two-slope density profile can lead to absolutely unstable solutions in a three-wave coupling system

$$\left(\frac{\partial}{\partial t}+V_1\frac{\partial}{\partial x}\right)a_1=\gamma_0 a_2 e^{i\varphi(x)}$$

$$\left(\frac{\partial}{\partial t}+V_2\frac{\partial}{\partial x}\right)a_2=\gamma_0 a_1 e^{-i\varphi(x)}$$

$$\varphi(x)=\frac{1}{2}\kappa'(1-s)x^2$$



$$\frac{\partial^2}{\partial z_-^2}a+\left(\frac{1}{2}-i\Lambda-\frac{1}{4}z_-^2\right)a=\frac{\gamma_0 a_{20}\delta(x)}{V_1V_2},\quad \Lambda=\frac{\gamma_0^2}{\left|\kappa' V_1 V_2\right|}$$

Solution:

$$\begin{cases}\phi_-(x,p)=D_{i\Lambda-1}(iz_-), & x<0\\ \phi_+(x,s,p)=D_{-i\Lambda/(1-s)}(z_+), & x>0\end{cases}$$

Connect the solutions at $x = 0$:

$$a(x,p)\propto\frac{\phi_-(x,p)\,\phi_+(0,s,p)\,\theta(-x)+\phi_+(x,s,p)\,\phi_-(0,p)\,\theta(x)}{\phi_+(0,s,p)\frac{\partial}{\partial x}\phi_-(0,p)-\phi_-(0,p)\frac{\partial}{\partial x}\phi_+(0,s,p)}$$

Singularity in p complex plane with real $(p) > 0$ → **Absolute growth**

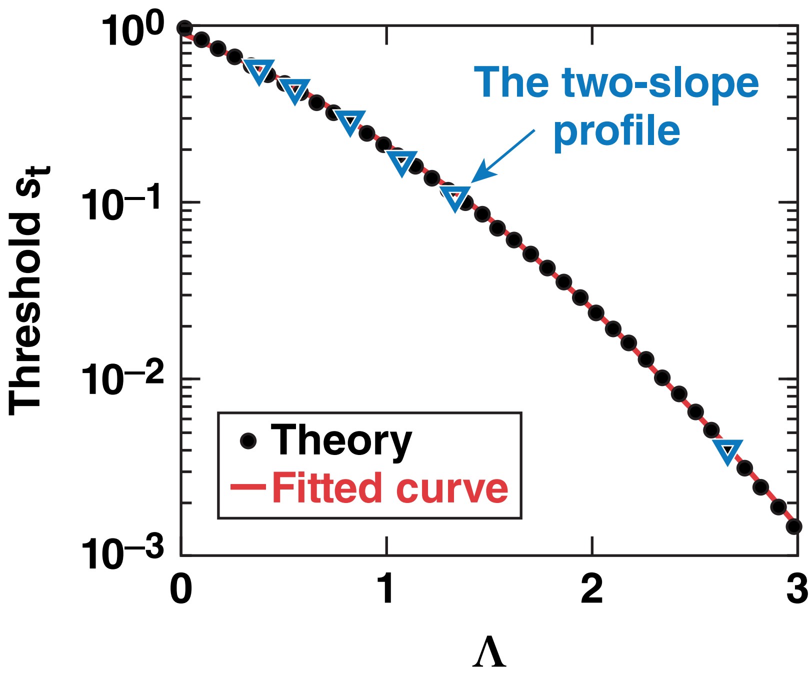
TC12789

An analytical expression is derived for the threshold of the gradient change

$$\sqrt{1-s_t}\,\frac{D'_{-i\Lambda/(1-s_t)}\left[\frac{e^{i5\pi/4}}{\sqrt{2(1-s_t)}}\right]}{D_{-i\Lambda/(1-s_t)}\left[\frac{e^{i5\pi/4}}{\sqrt{2(1-s_t)}}\right]} = i\,\frac{D'_{i\Lambda-1}\left(\frac{e^{i7\pi/4}}{\sqrt{2}}\right)}{D_{i\Lambda-1}\left(\frac{e^{i7\pi/4}}{\sqrt{2}}\right)}$$

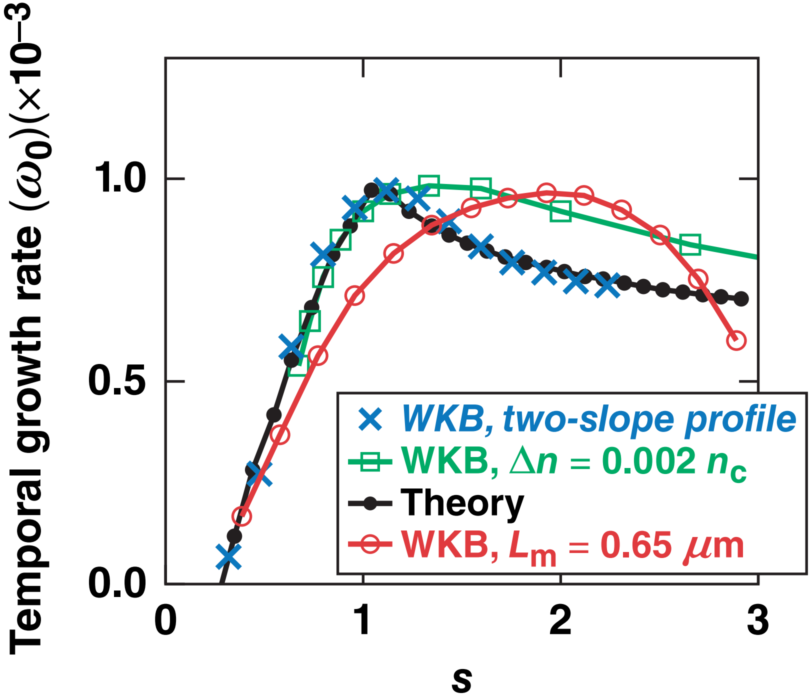
Fitted:

$$s_t(\Lambda) = \exp(-0.35\,\Lambda^2 - 1.1\Lambda - 0.1)$$

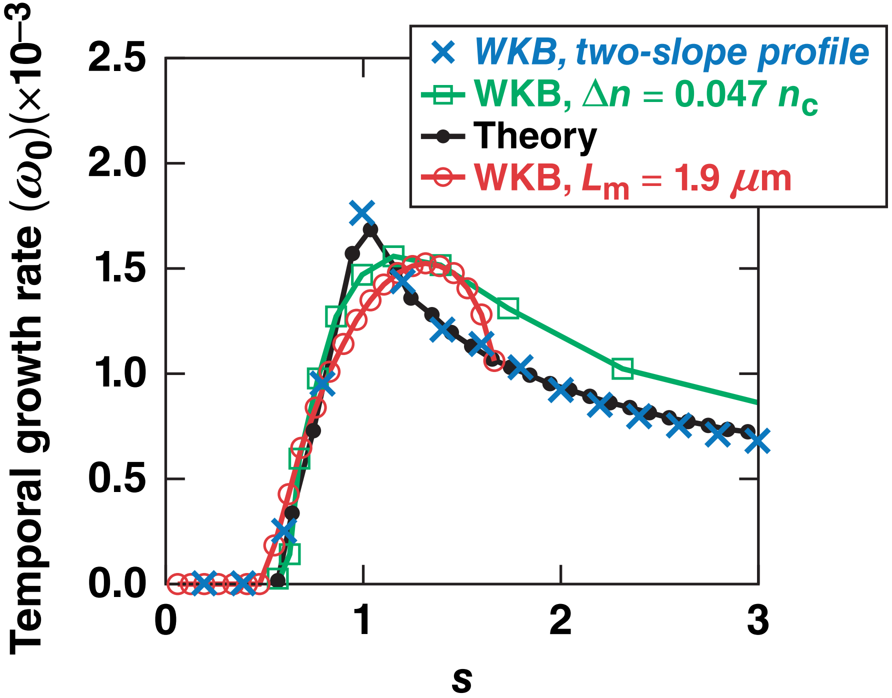


- The threshold s_t depends only on the gain parameter Λ

The two-slope model can be used to assess the maximum growth rates of the density-modulation–induced absolute modes for a given density profile



TPD: $I = 6 \times 10^{14}$ W/cm^2, $n_e = 0.235\ n_c$



SRS: $I = 2 \times 10^{15}$ W/cm^2, $n_e = 0.22\ n_c$

$$n_1 = \Delta n \sin(x/L_m) \Rightarrow \Delta k = k_m \sin\frac{x}{L_m} \Rightarrow s \leftrightarrow \frac{k_m}{L_m \kappa'} \propto \frac{\Delta n}{L_m}$$

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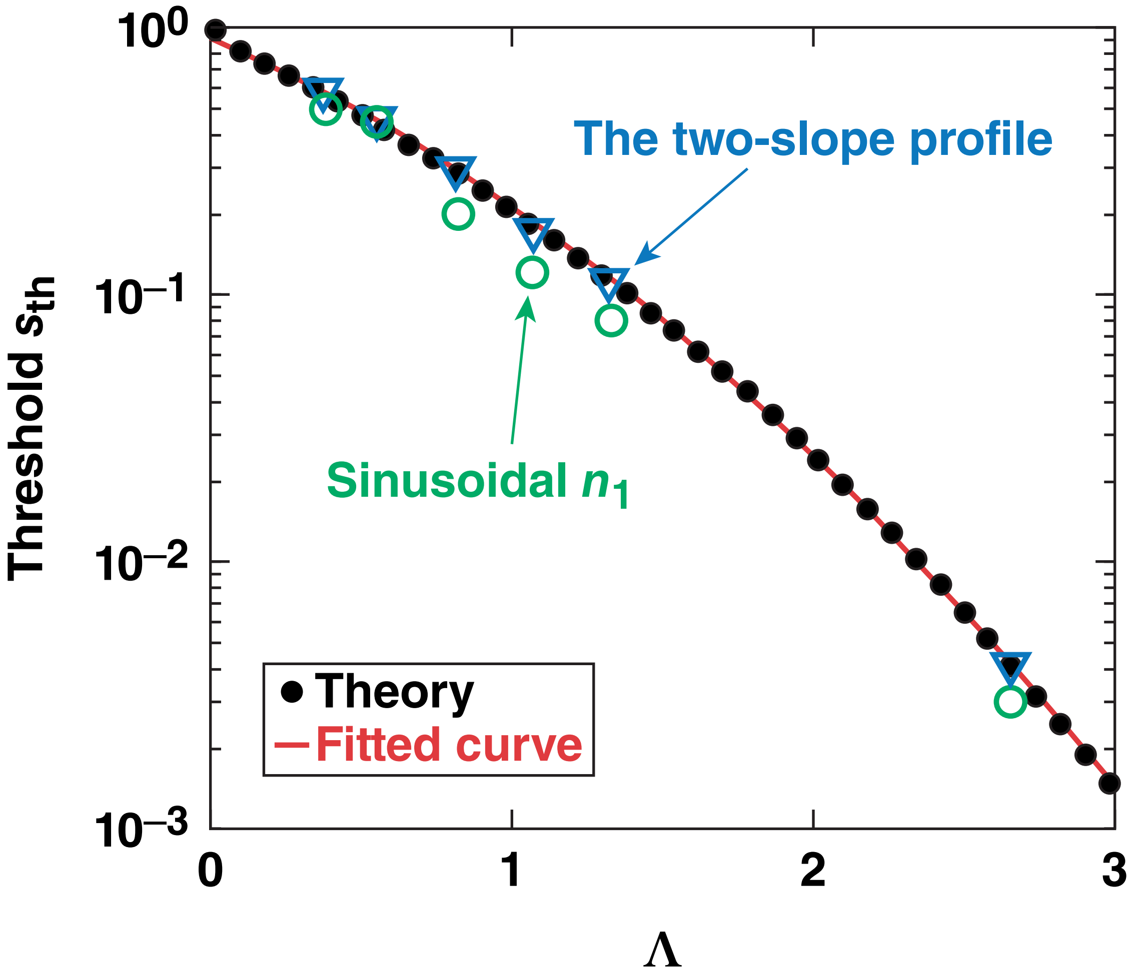
The threshold formula of "s" works for sinusoidal density-modulation–induced absolute modes



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