Vlasov Simulations of Kinetically-Enhanced Raman Backscatter and Electron Acoustic Thomson Scattering

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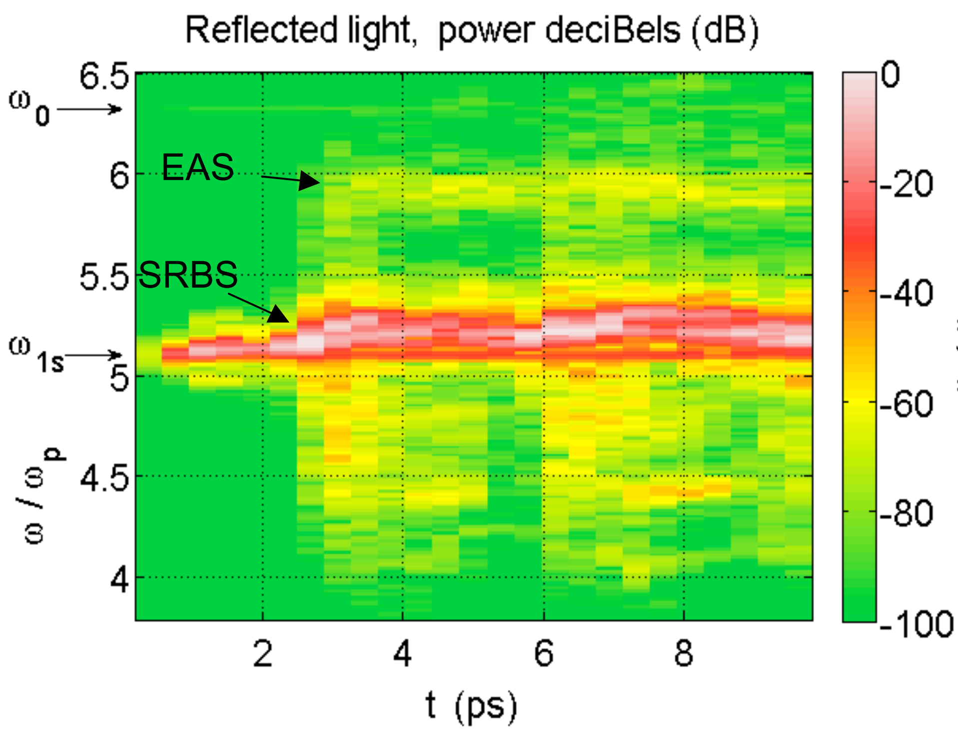

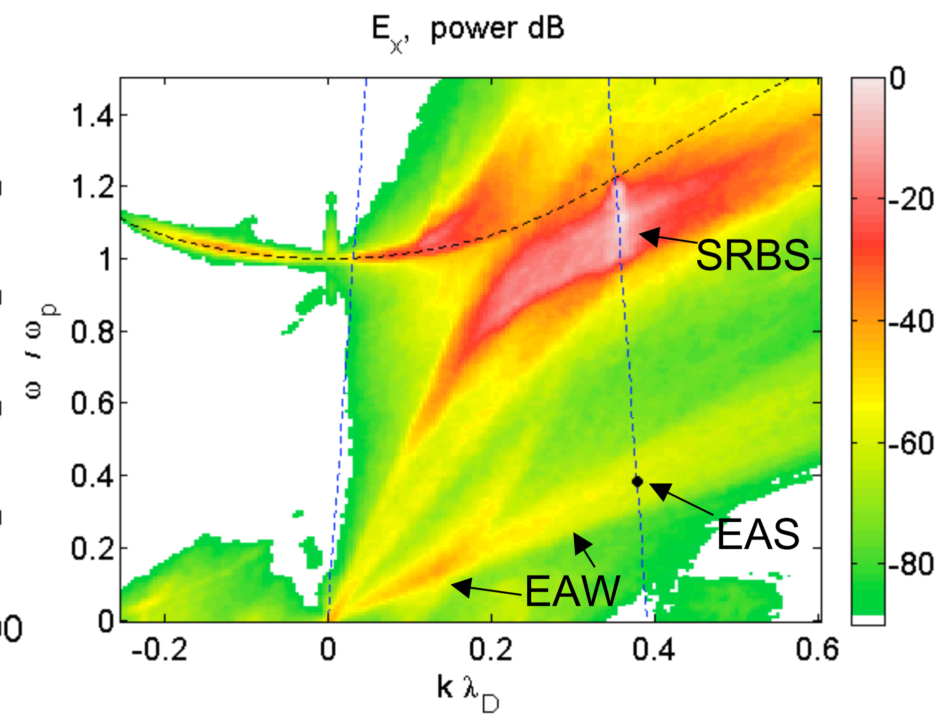

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Outline

- **Experimental motivation - Trident single hot spots[1,2]**
  - **- Kinetic inflation[3] of stimulated Raman backscatter (SRBS)**
  - **- Stimulated (?) electron acoustic scattering (SEAS) off electron acoustic wave (EAW)**

- **ELVIS[4] Vlasov-Maxwell simulations:**
  - **- SRBS kinetic enhancement**
  - **- Beam acoustic modes (BAMs)[5] develop; SRBS off one of them**
  - **- electron acoustic wave (EAW), electron acoustic scatter (EAS), from self-consistent SRBS physics**

- **EAWs excited by beam acoustic decay (BAD): BAM → BAM + EAW**
  - **- may be two-pump: BAM's beat to make EAW**
  - **- EAW curve weakly excited by harmonic generation**

- **Electron acoustic Thomson scattering (EATS)**
  - **- EAS not exciting EAW, but is Thomson scattering off EAW fluctuations from BAD**

- **Linear modes (Hermite-Gauss projection) match simulation spectrum**
  - **- Series of BAMs, some unstable (without parametric coupling)**
  - **- Heavily-damped EAW; different from trapped EAWs of Rose[6]**

- **Bispectral analysis: BAD-EATS frequency matching found, phase coupling weak.**

- **BAM, BAD, EATS similar in hohlraum regimes (high temperature, high density).**

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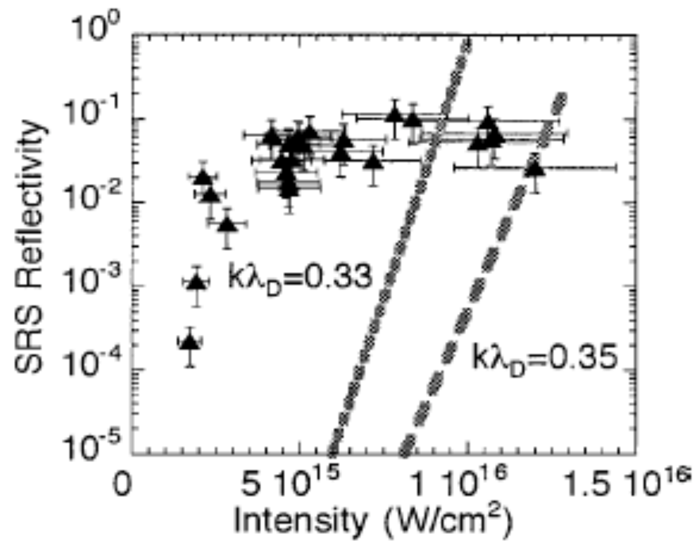
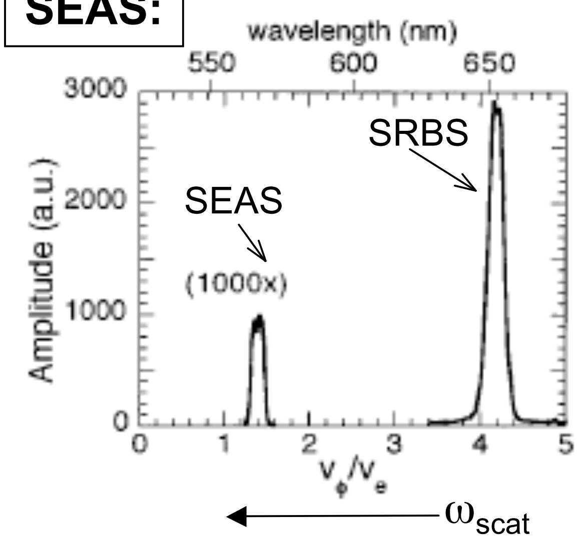
[1]D. S. Montgomery et al., *Phys. Plasmas* **9**, 2311 (2002); [2]J. L. Kline et al, *Phys. Rev. Lett.* **94**, 175003 (2005);
[3]H. X. Vu et al., *Phys. Rev. Lett.* **86**, 4306 (2001); [4]D. J. Strozzi et al., *J. Plasma Phys.*, accepted (2006);
[5]L. Yin et al., *Phys. Rev. E* **73**, 025401 (2006); [6]H. A . Rose and D. A. Russell, *Phys. Plasmas* **8**, 4784 (2001).

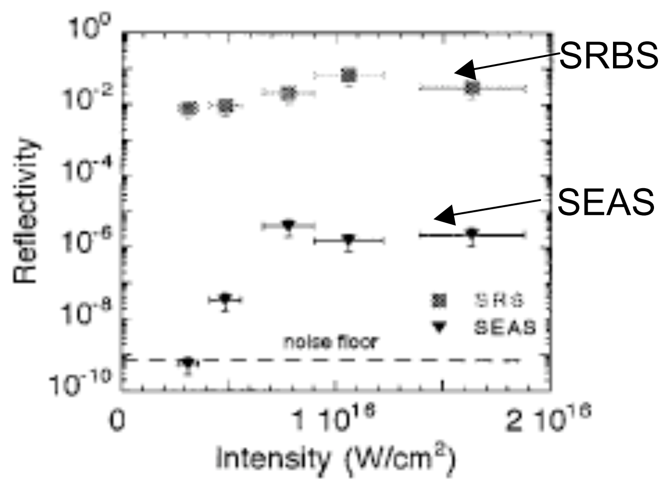
Motivation: single-hot-spot experiments (Trident) show enhanced SRBS and stimulated (?) electron acoustic scatter (SEAS)

enhanced SRBS:



SEAS:



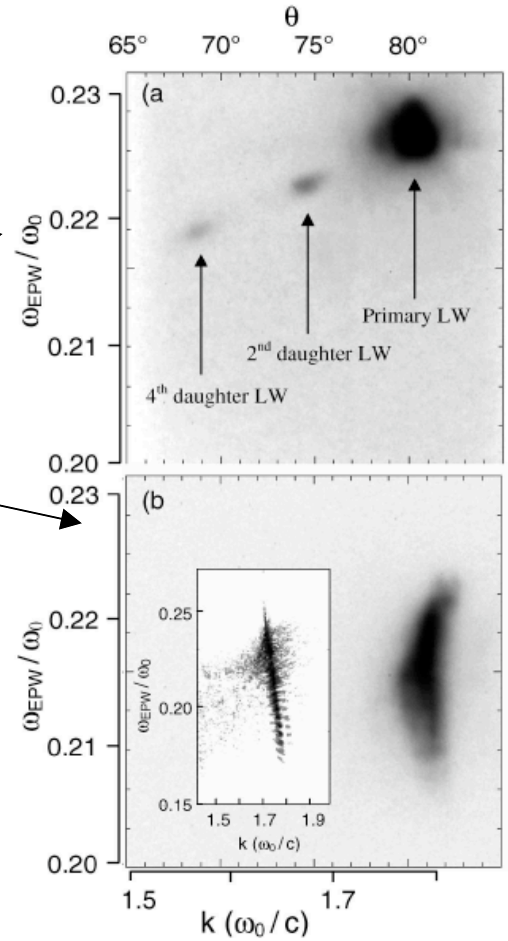


[D. S. Montgomery et al., *Phys. Plasmas* **9**, 2311 (2002)]

LDI vs trapping:

lower k

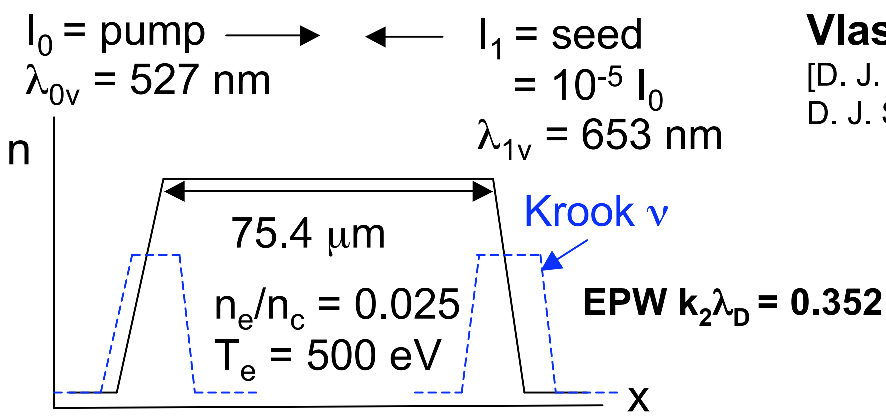
higher k



[J. L. Kline et al, *Phys. Rev. Lett.* **94**, 175003 (2005)]

ELVIS Vlasov simulations: SRBS bursty, kinetically enhanced above linear gain level

“Trident” Parameters



Simulations with 1-D Eulerian Vlasov-Maxwell solver ELVIS; fixed ions.

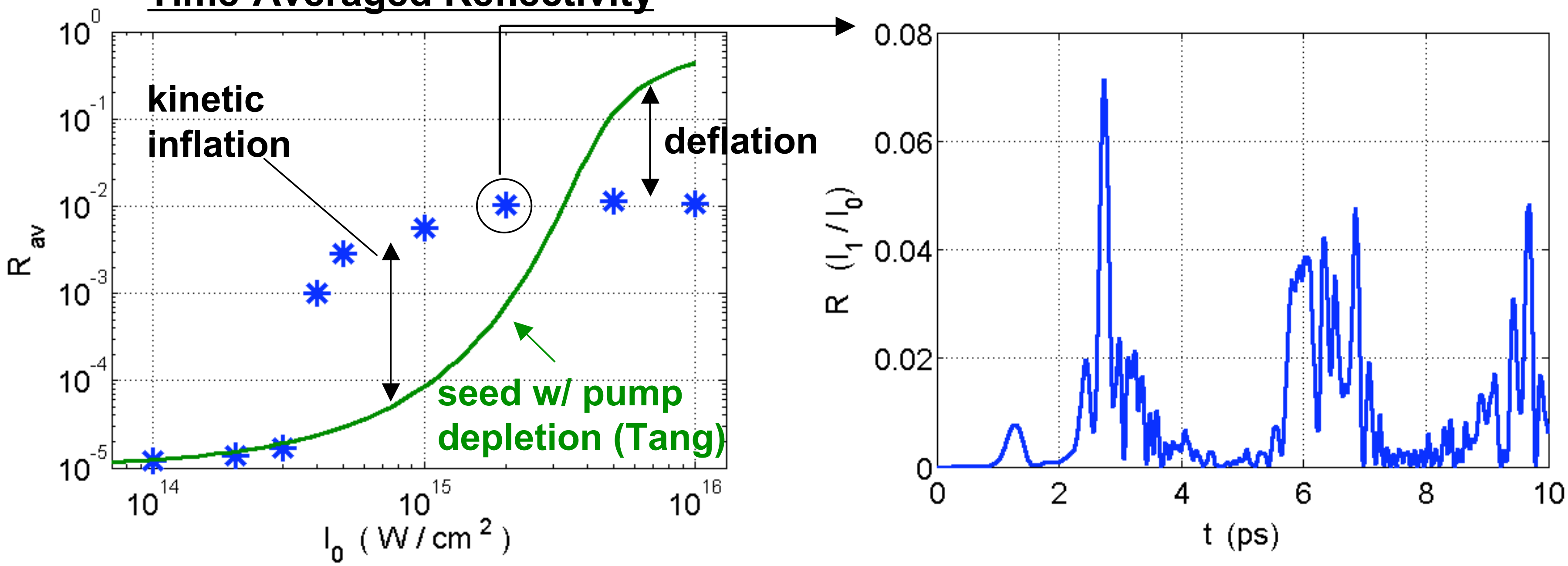
[D. J. Strozzi et al., *J. Plasma Phys.*, accepted 2005; D. J. Strozzi et al., *Comput. Phys. Comm.* **164**, 156 (2004)]

$I_0 = 2 \cdot 10^{15}$ W/cm^2

amp. gain rate = 0.0289 μm^{-1}, intensity gain = 4.36, R_{av} = 7.81•10^{-4}

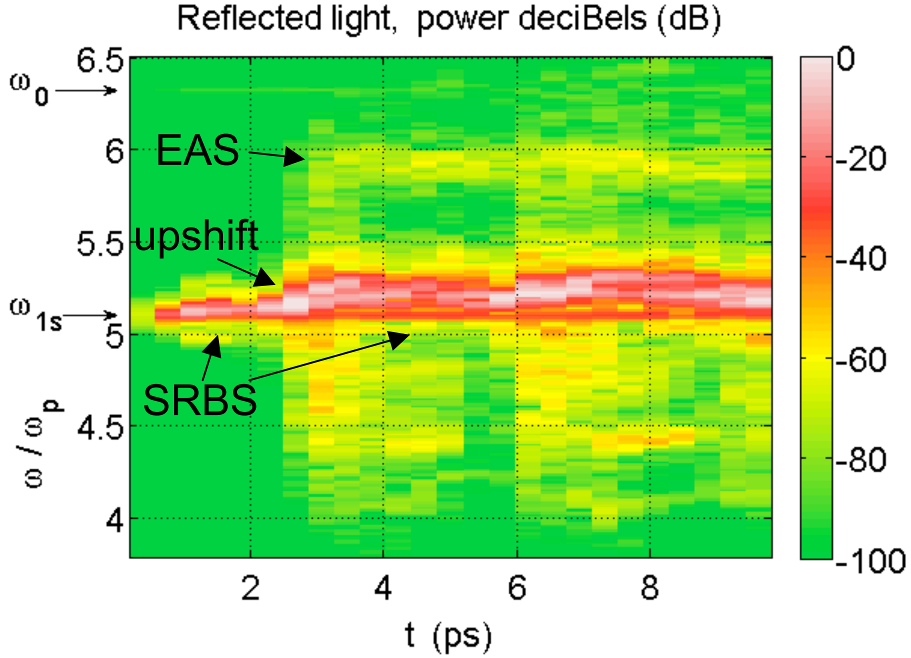
simulation R_{av} = 1.03%

Time-Averaged Reflectivity



Reflected light: SRBS upshifts due to electron trapping; electron acoustic scatter (EAS) develops after kinetic enhancement

Trident, $I_0 = 2 \cdot 10^{15}$ W/cm²

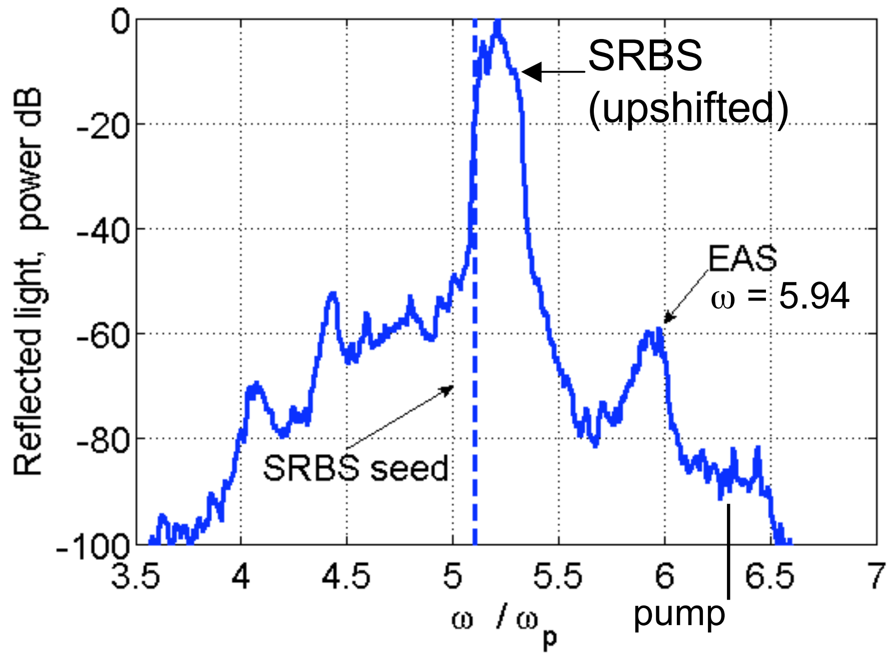


Electron trapping in Raman plasmon reduces Landau damping, gives kinetic enhancement.

Trapping also downshifts the plasmon frequency, which upshifts scattered light.

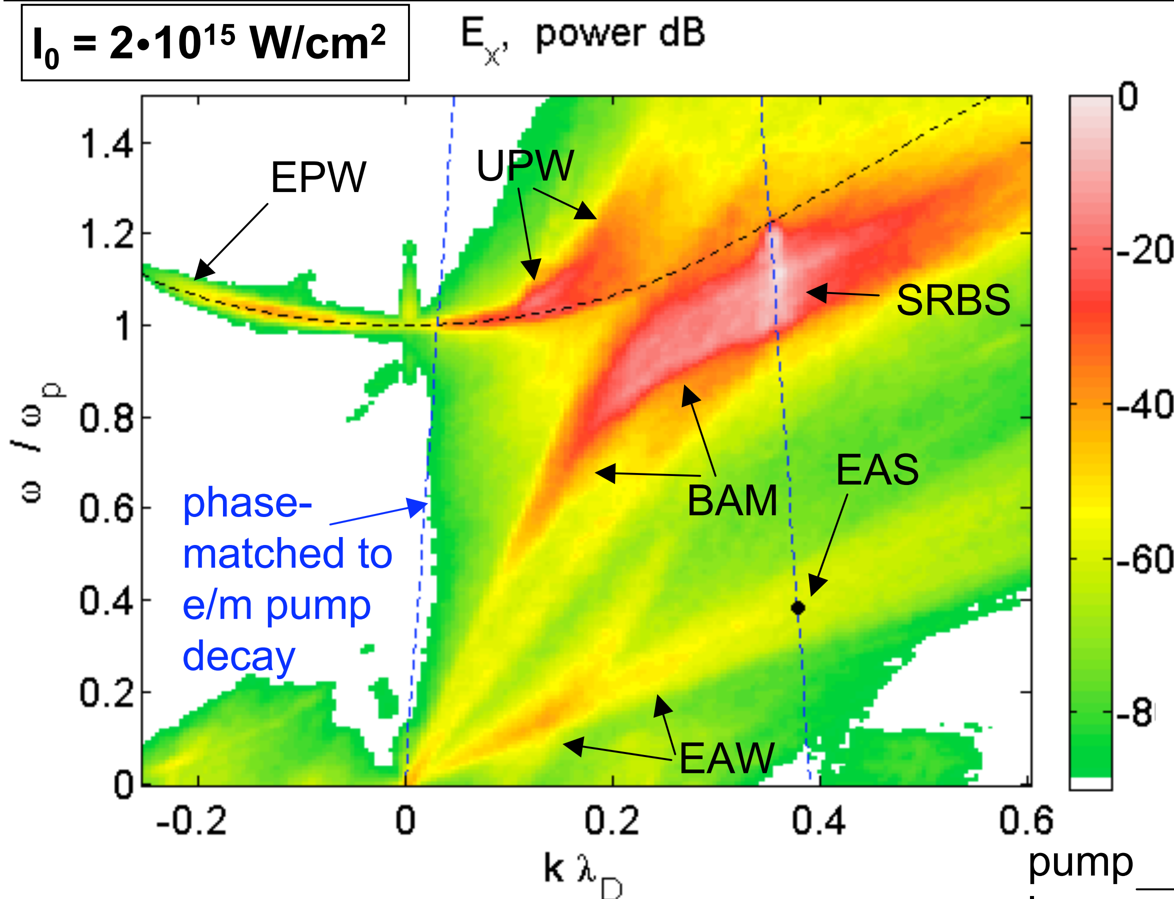
[T. O'Neil, *Phys. Fluids* **8**, 2255 (1965);
G. J. Morales and T. M. O'Neil, *Phys. Rev. Lett.* **28**, 417 (1972);
H. X. Vu et al., *Phys. Rev. Lett.* **86**, 4306 (2001)]

Time-integrated spectrum

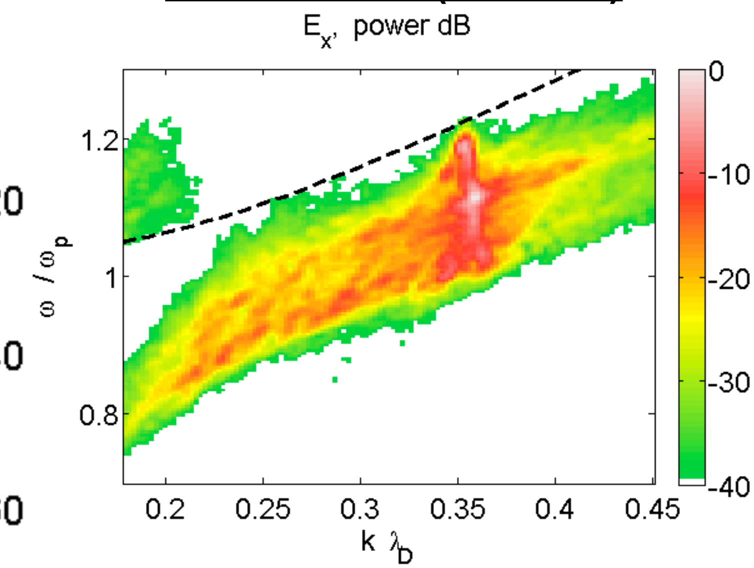


Electrostatic spectrum shows plasmon downshift, electron acoustic waves

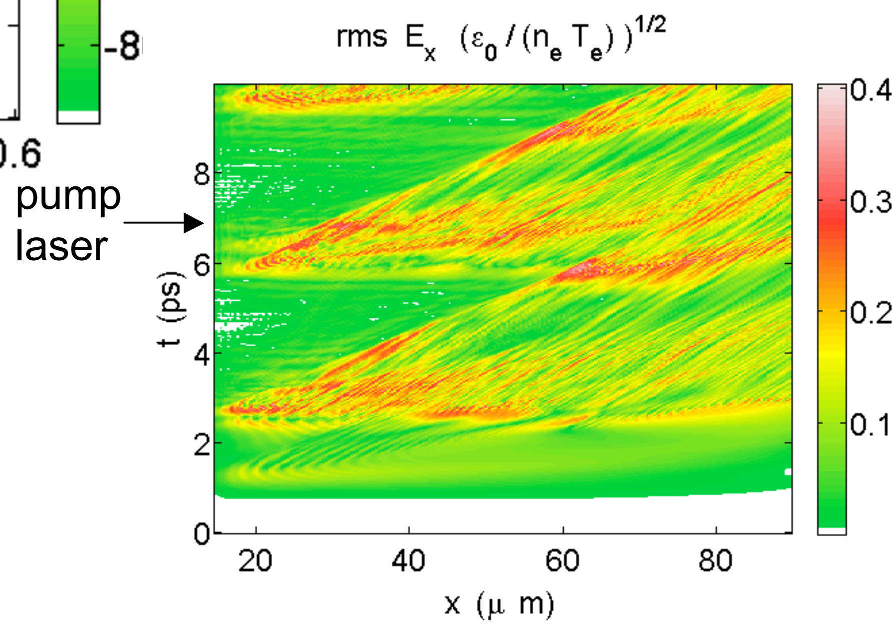
$I_0 = 2 \cdot 10^{15}$ W/cm²



SRBS streak (zoomed)

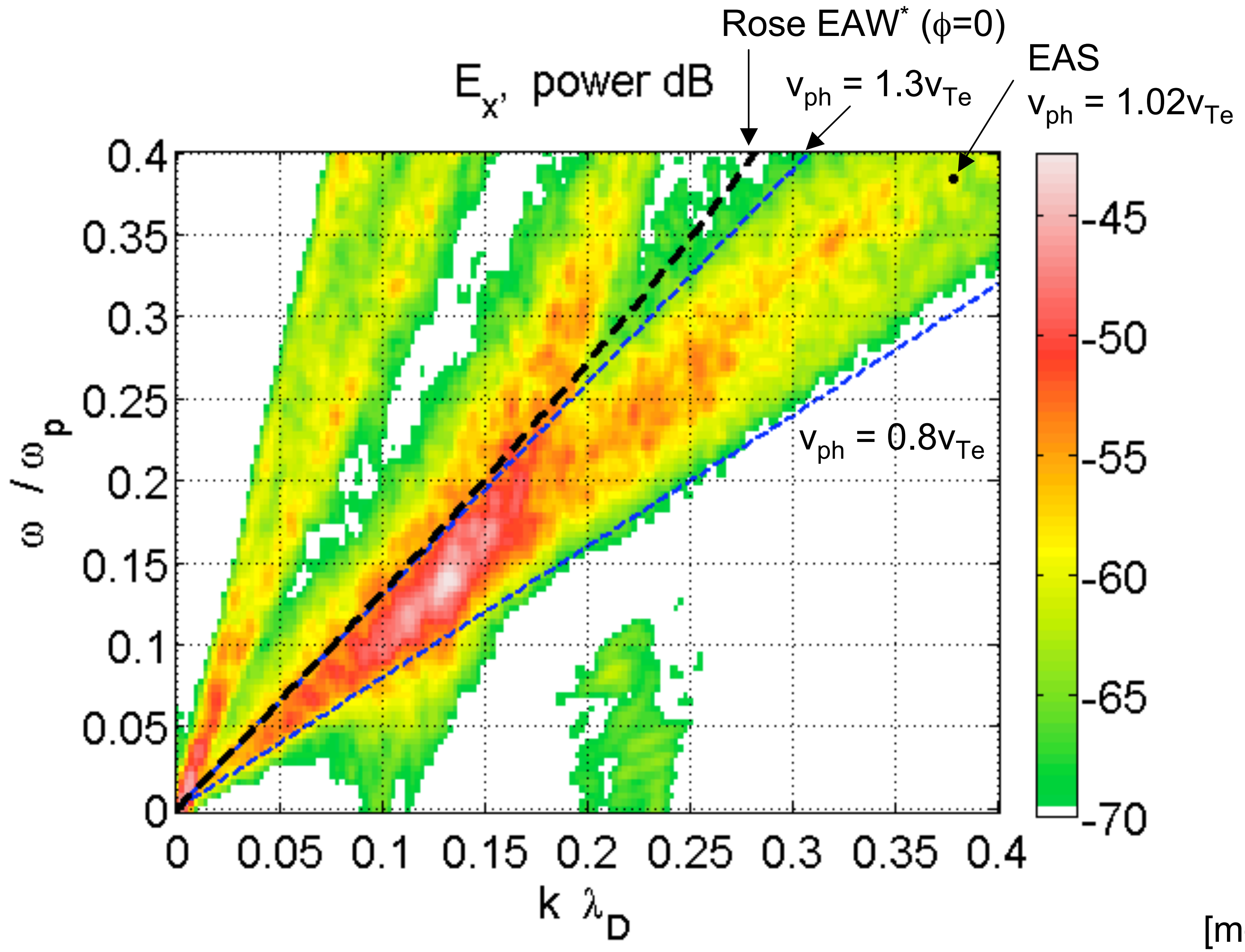


electrostatic envelope



- **SRBS plasmon downshifts in ω due to trapping.**
- **Linear EPW curve 'splits' into two branches.**
- **Beam acoustic modes (BAMs) observed, similar to L. Yin et al., *Phys. Rev. E* 73, 025401 (2006).**
- **Electron acoustic waves (EAWs) excited mostly for $k\lambda_D < 0.2$, well below EAS matching point.**

Electron acoustic wave (EAW) strongest well below EAS matching frequency; different from Rose trapped EAW

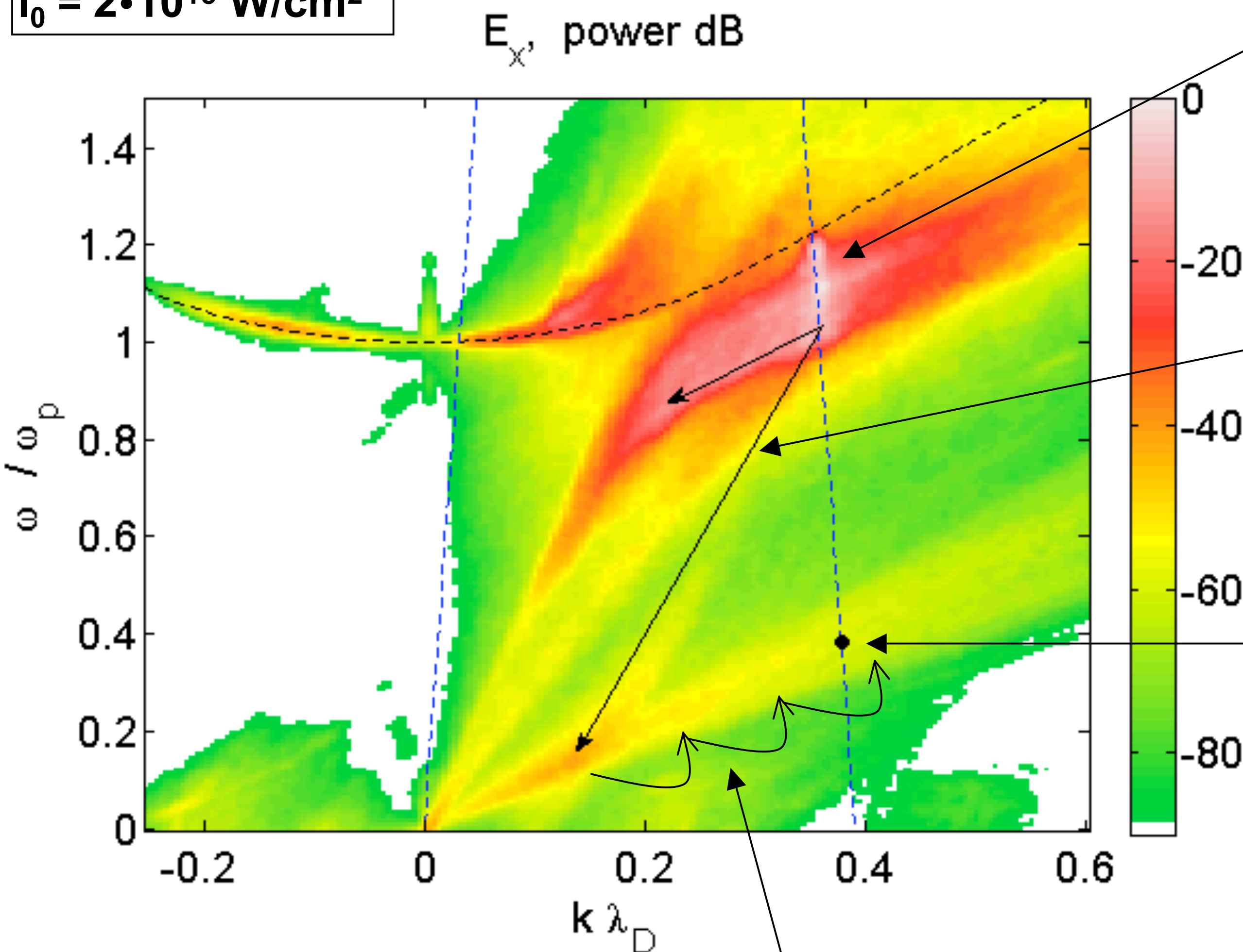


[movie]

*H. A . Rose and D. A. Russell, *Phys. Plasmas* **8**, 4784 (2001). EAW phase velocity increases with amplitude.

Beam acoustic decay (BAD) - electron acoustic Thomson scatter (EATS)

$I_0 = 2 \cdot 10^{15}$ W/cm²



1. SRBS develops; ω downshifts due to trapping; some BAMs unstable.

2. beam acoustic decay (BAD): BAM → BAM + EAW*.

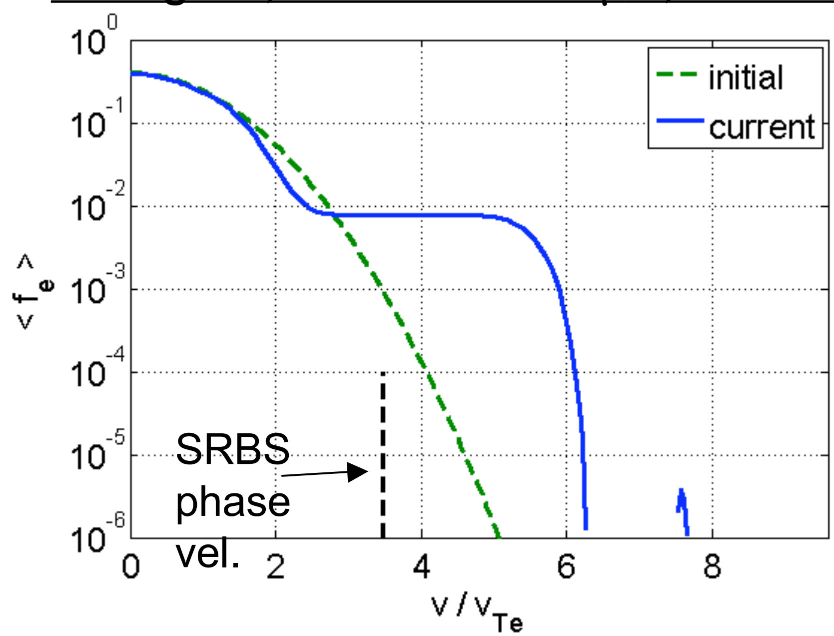
4. pump laser scatters off EAW fluctuations: electron acoustic Thomson scatter (EATS).

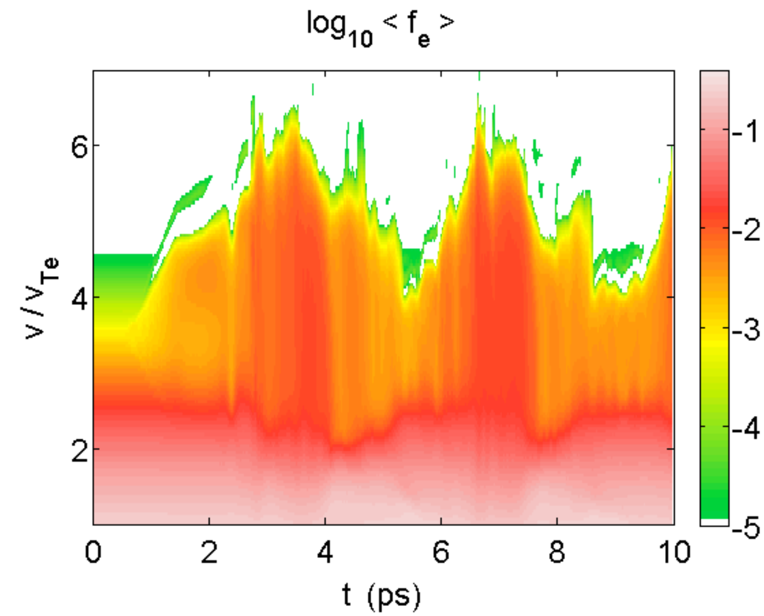
3. harmonic coupling energizes EAW at higher k.

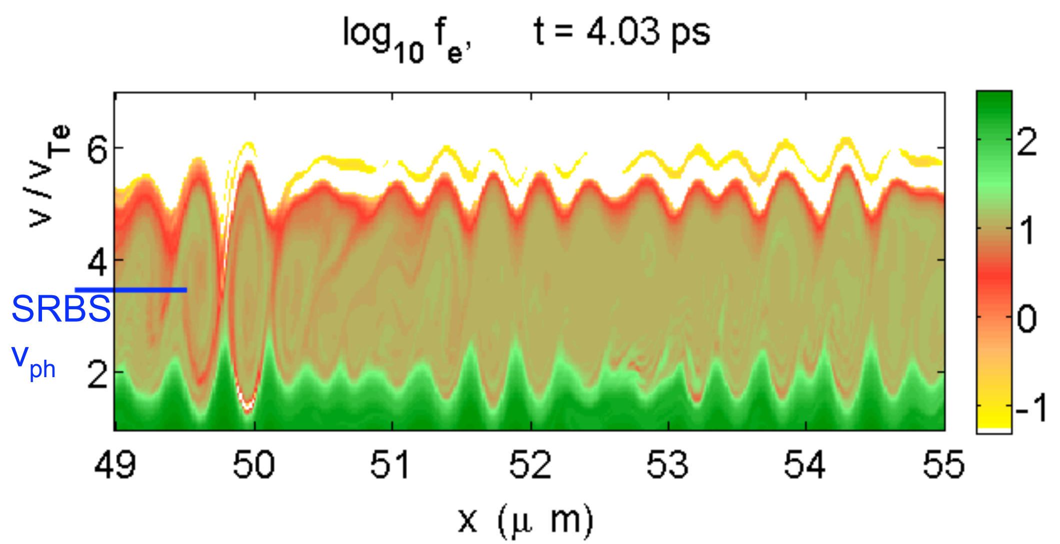
*Displayed BAD involves an EAW with phase velocity 1.14 v_{Te}

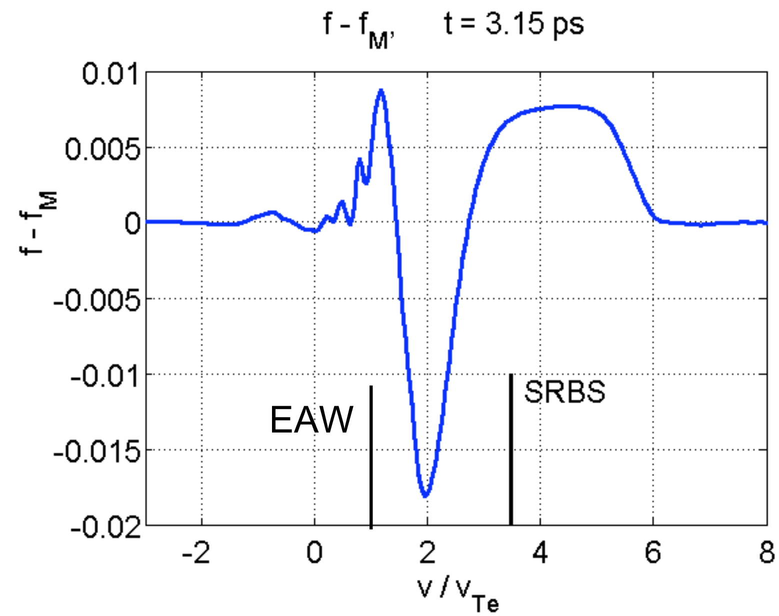
Distribution function shows vortices and persistent flattening, roughly tied to wave amplitude ($I_0 = 2 \cdot 10^{15}$ W/cm^2)

averaged f, x = 50.6 : 53.8 μm, t = 3.15 ps









Hermite projection yields linear modes of arbitrary distribution

- **Hermite projection:**

$$f(v) = \sum_{n=0}^{N} f_n \phi_n(v) \qquad \phi_n(v) = \frac{1}{\pi^{1/4}\sqrt{2^n n!}} H_n(v)\exp(-v^2/2)$$

$$f_n = \int_{-\infty}^{\infty} dv\, \phi_n(v) f(v)$$

$$\chi(v_p) = -k^{-2} \sum f_n \chi_{vn}(v_p) \qquad \chi_{vn}(v_p) = \frac{d}{dv_p} \int dv \frac{\phi_n(v)}{v - v_p}$$

$$\omega_{pe} = \lambda_{De} = v_{Te} = 1$$
$$v_p = \omega/k$$

- **Recurrence relation:**

$$\chi_{vn} = -\left(\frac{2}{n}\right)^{1/2} \chi'_{v,n-1} + \left(\frac{n-1}{n}\right)^{1/2} \chi_{v,n-2}, \qquad n \geq 2$$

$$\chi_{v0} = \frac{\pi^{1/4}}{\sqrt{2}} Z'(v_p/\sqrt{2}) \qquad \chi_{v1} = -\frac{\pi^{1/4}}{\sqrt{2}} Z''(v_p/\sqrt{2})$$

- **Upshot:**

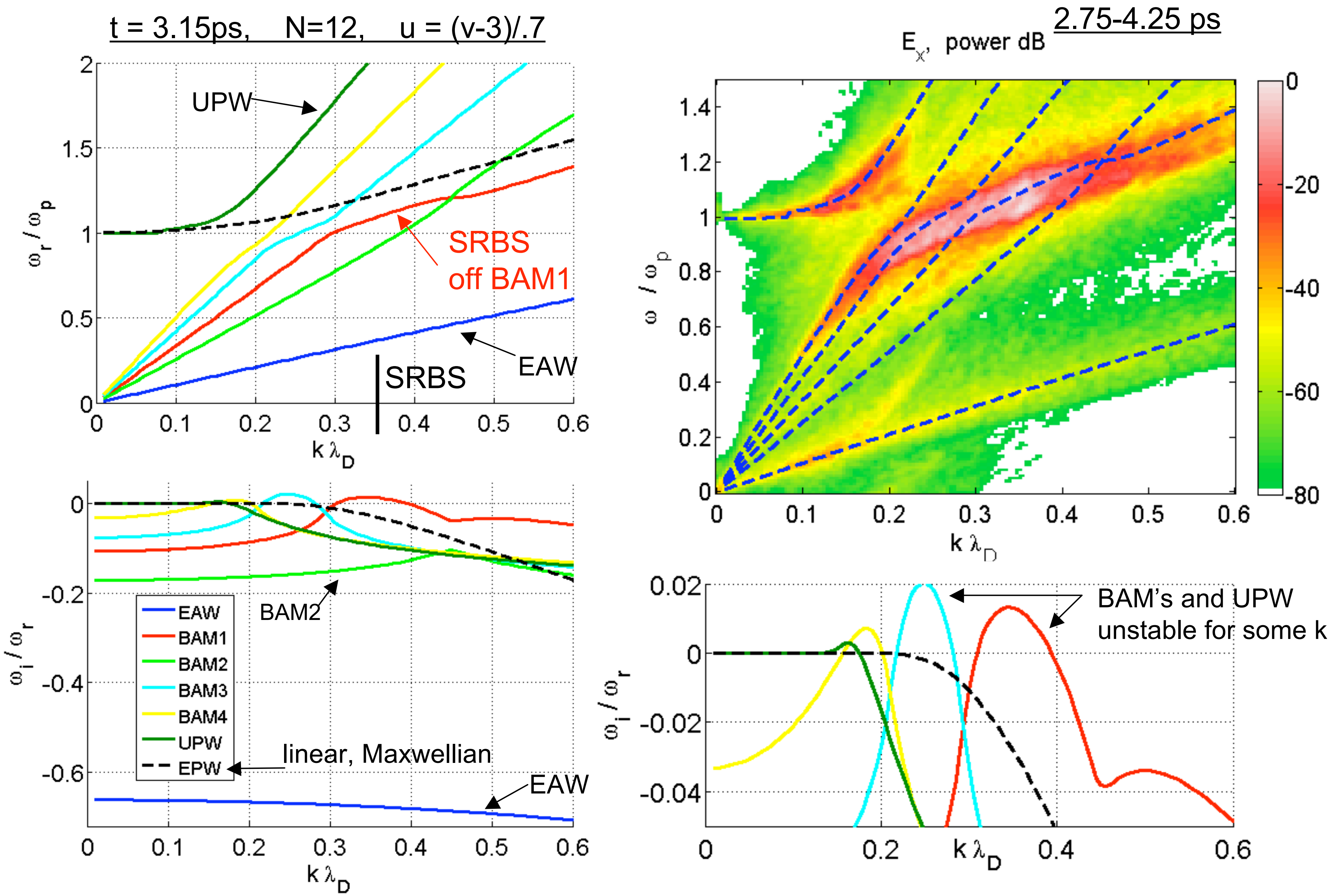
$$\chi_{vn}(v_p) = P_{Z,n+1}(v_p) Z\left(v_p/\sqrt{2}\right) + P_{R,n}(v_p)$$

$P_{Z,n}$, $P_{R,n}$ = N^{th} order polynomials

- **Dispersion relation (no parametric coupling):**

$$1 + \chi = 0$$

Roots vs. k agree with observed electrostatic spectrum ($I_0 = 2{\cdot}10^{15}$ W/cm^2)



Bispectral analysis measures frequency-matched, phase-locked signals

x, y, z = real; stationary; zero mean: cumulants = moments through 3rd order

- **2-point correlation (order 2 cumulant):** $C_2(\tau) = \frac{1}{2T}\int_{-T}^{T} dt\, x(t)y(\tau+t)$

- **Power spectrum (Wiener-Khinchin):** $P_2(\omega) = \int_{-\infty}^{\infty} d\tau\ e^{-i\omega t} C_2(\tau) = < X^*(\omega)Y(\omega) >$

- **3-point correlation function:** $c_3(\tau_1,\tau_2) = \frac{1}{2T}\int_{-T}^{T} dt\, x(t)y(\tau_1+t)z(\tau_2+t)$

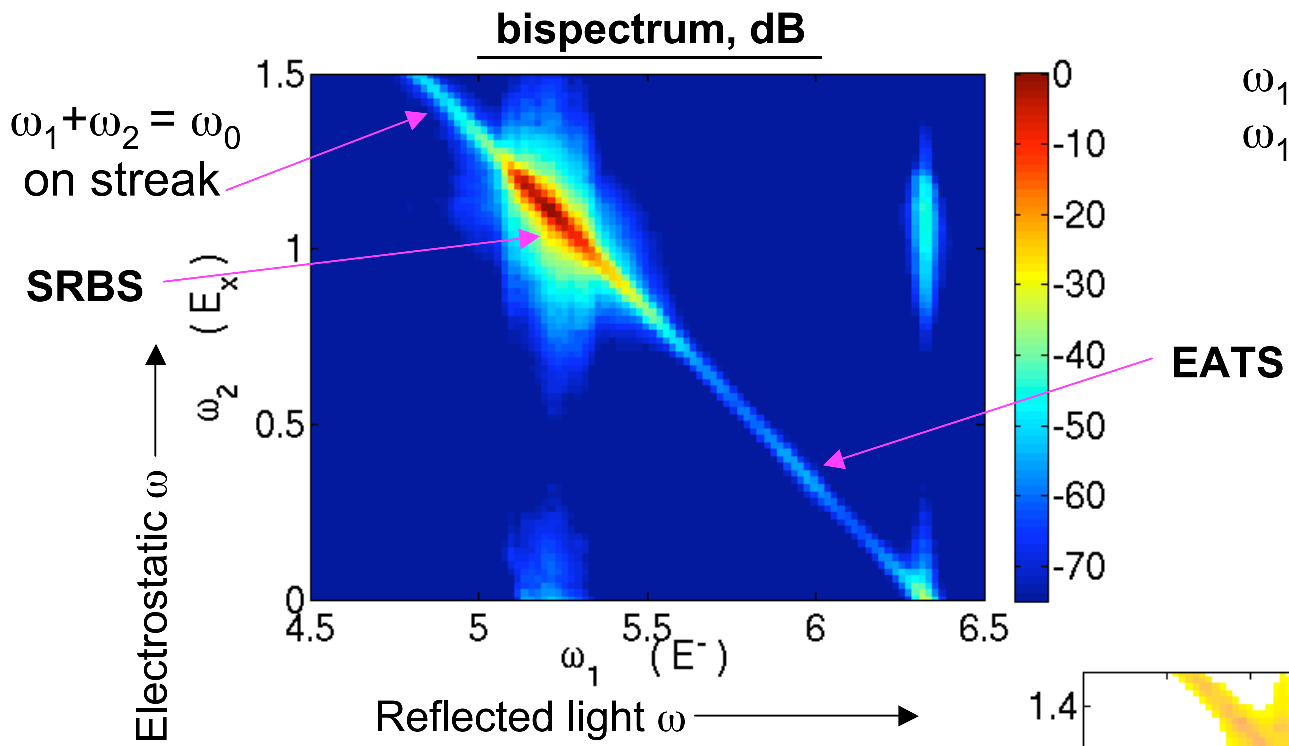
- **bispectrum:**
  (complex; phase info): $P_3(\omega_1,\omega_2) = \int_{-\infty}^{\infty} d\tau\, e^{-i(\omega_1\tau_1+\omega_2\tau_2)} C_3(\tau_1,\tau_2)$

$$P_3(\omega_1,\omega_2) = < X^*(\omega_1+\omega_2)Y(\omega_1)Z(\omega_2) >$$

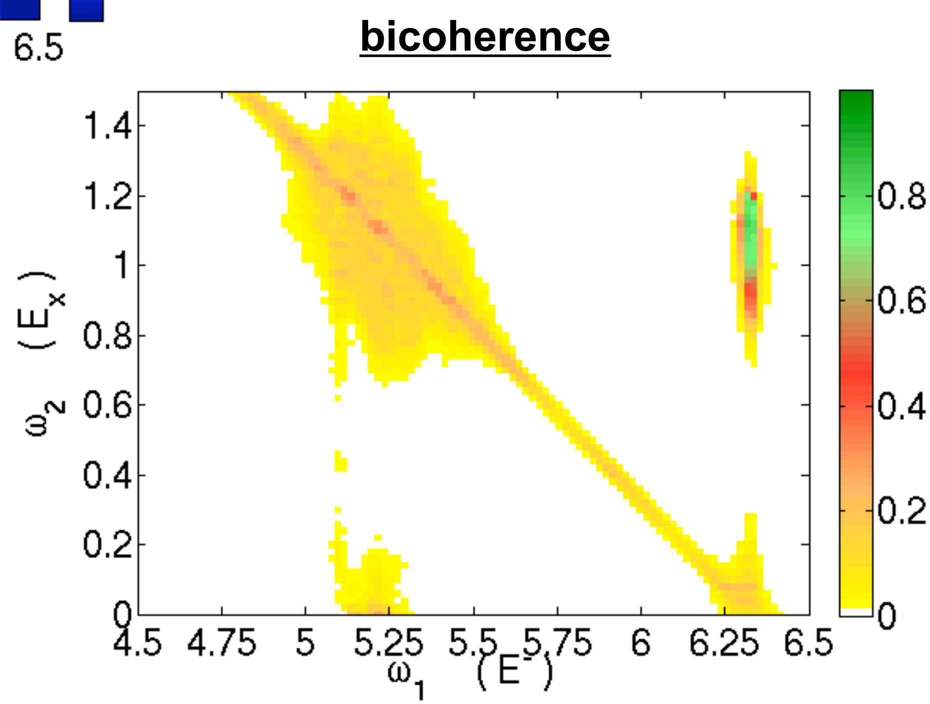
- **bicoherence:**
  (normed bispectrum) $0 \le |b_3| \le 1$

$$b_3(\omega_1,\omega_2) = \frac{P_3(\omega_1,\omega_2)}{\sqrt{< |X(\omega_1+\omega_2)|^2 >< |Y(\omega_1)Z(\omega_2)|^2 >}}$$ = $\frac{\textbf{phase-coupled power}}{\textbf{total power}}$

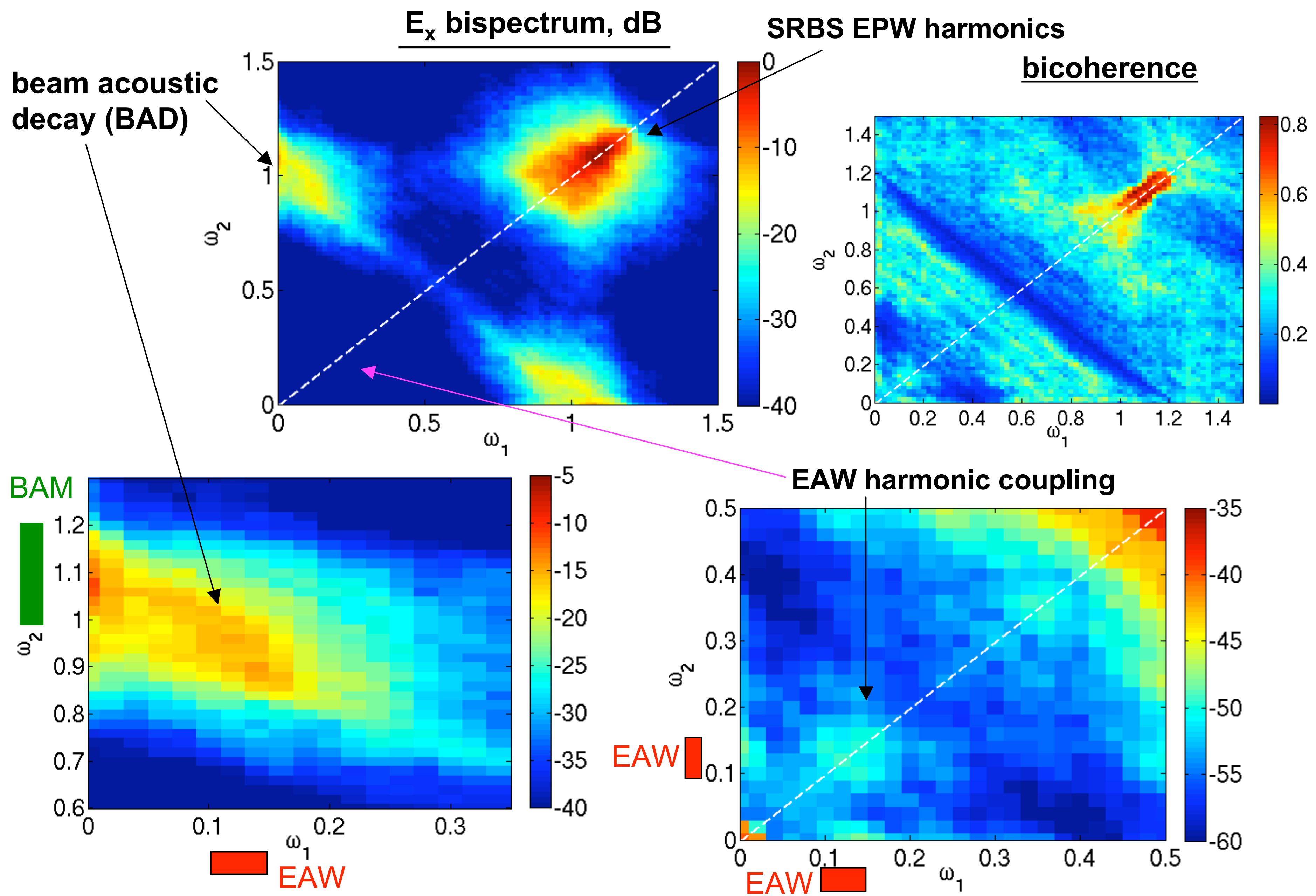
Bispectrum of $E^+(\omega_1+\omega_2)\ E^-(\omega_1)\ E_x(\omega_2)$: SRBS, EATS ($I_0 = 2\cdot10^{15}$ W/cm^2)



$\omega_1 + \omega_2$ (transmitted) =
ω_1 (reflected) + ω_2 (electrostatic)



E_x Bispectrum: beam acoustic decay, EAW harmonics ($I_0 = 2{\bullet}10^{15}$ W/cm^2)



Conclusions and future work

Conclusions

- Electron trapping leads to kinetically enhanced SRBS, plasmon frequency downshift, bursty time evolution.
- Beam acoustic modes (BAMs), electron acoustic waves (EAWs) and electron acoustic scatter (EAS) observed, both in Trident single-hot-spot and hohlraum fill conditions.
- Hermite projection: linear modes of numerical distribution contain BAMs, some of which are linearly unstable, and heavily-damped EAWs.
- EAWs are energized by beam acoustic decay (BAD): BAM $\rightarrow$ BAM + EAW.
- EAS is Thomson scatter of EAW fluctuations (EATS)

Future Work

- Rule of thumb for kinetic enhancement onset and reflectivity? Useful for designers.
- Experimental work: can EAWs, BAMs, EATS vs. SEAS mechanism be studied? EAS may be a miner's canary for (mild) kinetic enhancement.
- Ions: Not shown here; early work shows BAMs, EATS survives (see Strozzi Ph.D thesis, 2005).