Particle-In-Cell, fully kinetic scale modelling of solar radio bursts based on non-gyrotropic and plasma emission mechanisms

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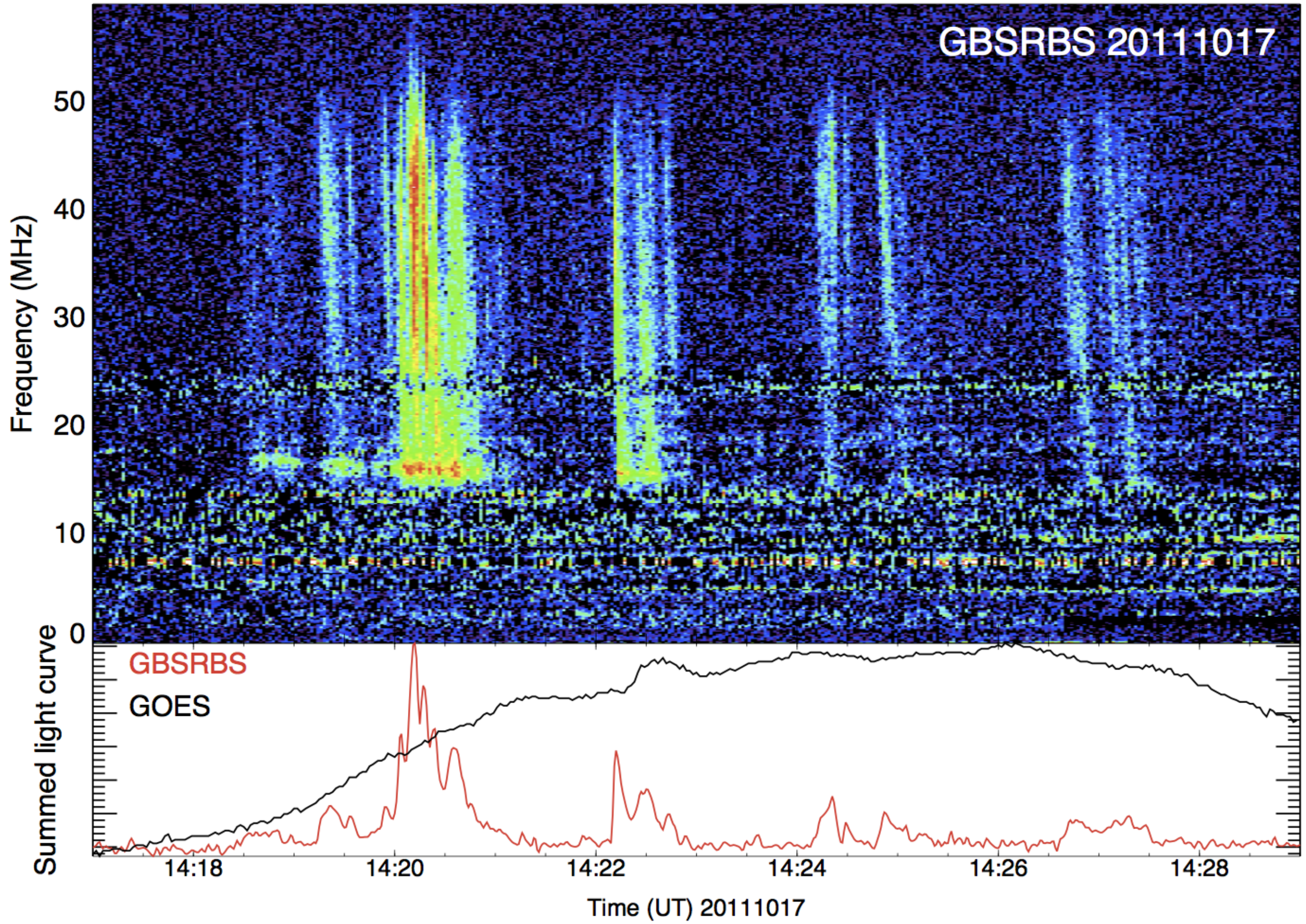
Type III burst Dynamical spectrum -- frequency vs time.



Type III solar radio burst, Green Bank SRB Spectrometer 17/10/2011. The rapid drift of the structures with time is clear, as is their occurrence during the impulsive phase of a solar flare (GOES X-ray flux increasing; bottom panel), http://www.transientskp.org/science/flarestars/

Basic physics of the radio emission mechanism (*plasma emission*):

*solar flares (i.e. reconnection) induce an electron beam;

*This generates Langmuir waves via bump-on-tail instability;

*Lamgmuir waves ($\approx \omega_{pe}$ and $2\omega_{pe}$) scatter off thermal ions or coalesce and produce EM emission at $\approx \omega_{pe}$ & $2\omega_{pe}$, respectively.

Good intro to mechanisms Malaspina et al. 2010 JGR, 115,A01101
cf. "antenna mechanism" and linear mode coupling on density gradient.
(i) Plasma emission proposed by Ginzburg & Zheleznyakov 1958;

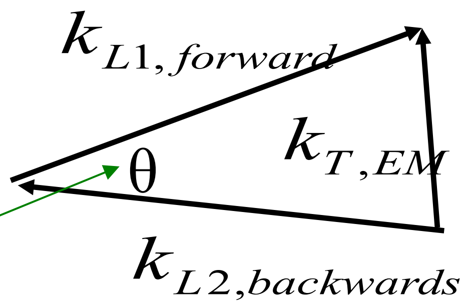
(ii) large, 1 AU-scale, phenomenological models based on Quasi-linear theory; Stochastic growth theory, Cairns & Robinson 1998, Li & Cairns, 2008, Reid & Kontar 2010.

(iii) small-scale, few 1000s Debye length = 10^{-10} AU, fully kinetic, Particle-In-Cell (PIC) simulation with self-consistent EM fields: Sakai et al (2005)+others, still based on plasma emission however.

* In the plasma emission mechanism, non-linear wave-wave interaction between Langmuir, ion-acoustic and EM waves requires the beat conditions to be satisfied. The emission formula (i.e. the three wave interaction probability) includes a cross vector product factor $|\vec{k}_L \times \vec{k}_T|^2$

The beat conditions for the three-wave interaction process

$$\omega_1 + \omega_2 = \omega_3$$
$$\vec{k}_1 + \vec{k}_2 = \vec{k}_3$$



* This implies that the correct treatment of the act of EM emission needs 2D spatial dimensions, i.e. θ must be non-zero!

* This poses serious computation limitation. Our aim is to find an EM emission mechanism that can do the job in 1.5D, since we know that EM emission of type III bursts have mostly k|| and nearly zero k-perp.

Study 1

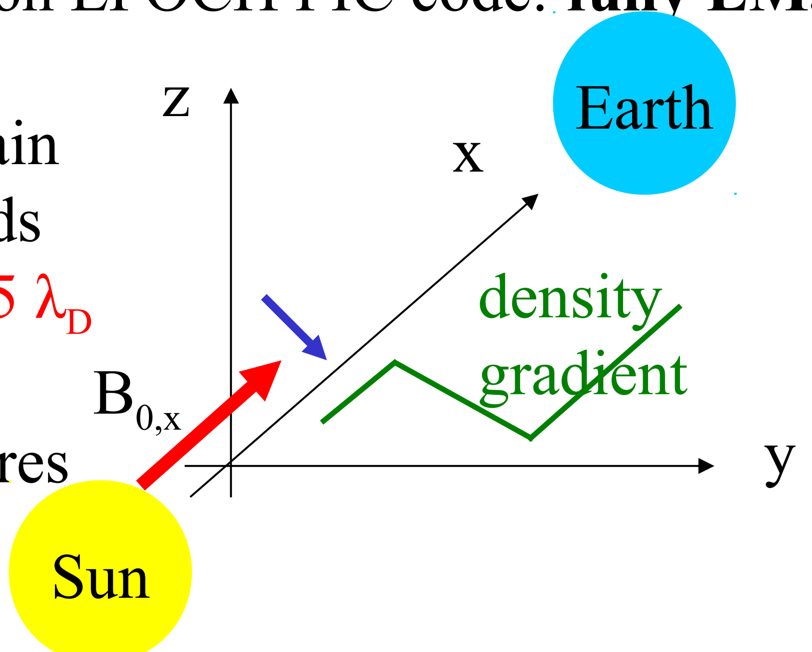
*Alternatives to plasma emission, such as non-gyrotropic electron beam:

D. Tsiklauri, Phys. Plasmas 18, 052903 (2011)
H. Schmitz, D. Tsiklauri, Phys. Plasmas, 20, 062903 (2013)
M. Skender, D. Tsiklauri, Phys. Plasmas 21, 042904 (2014)

Model is based on EPOCH PIC code: **fully EM, relativistic PIC code.**

Simulation domain size = 65000 grids
grid size 0.25-0.5 λ_D

each run: 512 cores 40 h, few x10^9 particles

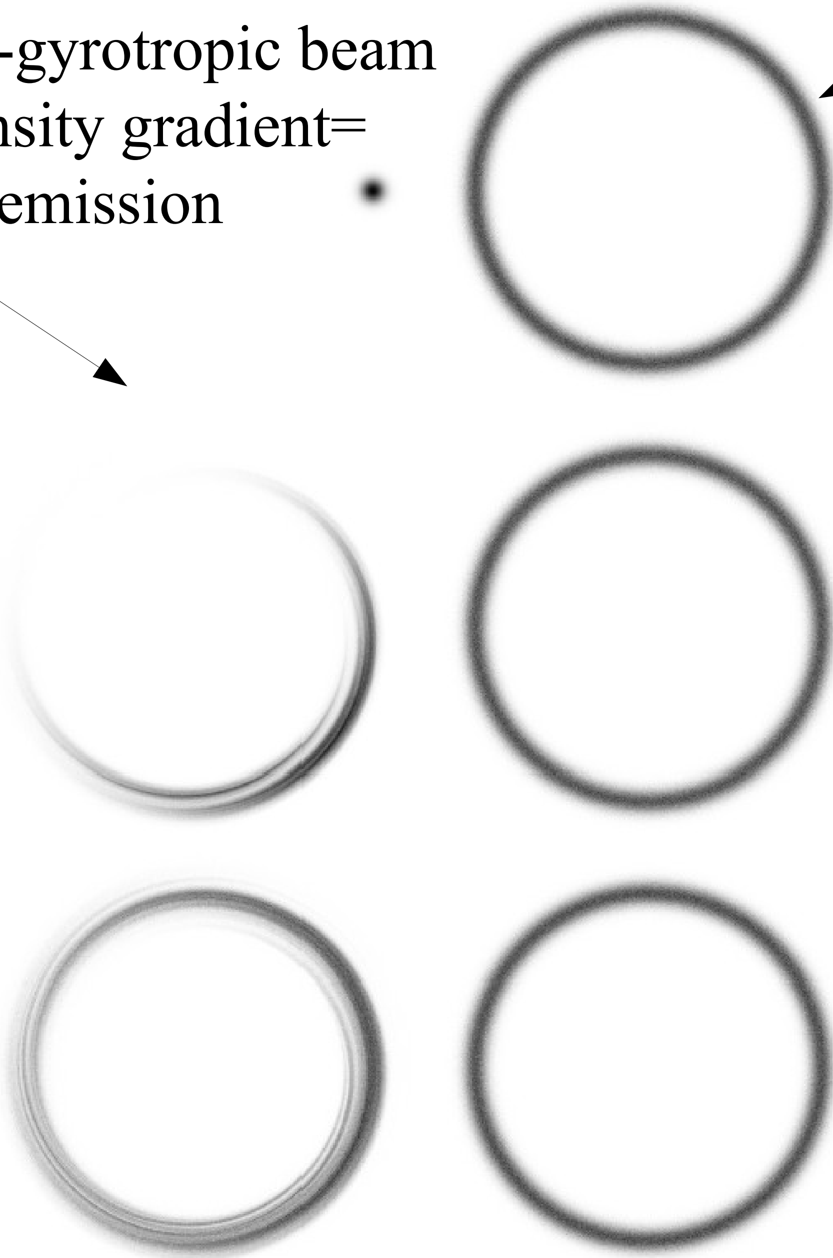


strongly magnetized case $\beta=1\times10^{-2}$.

k_{perp} is non-zero by setting 45^o beam pitch angle.

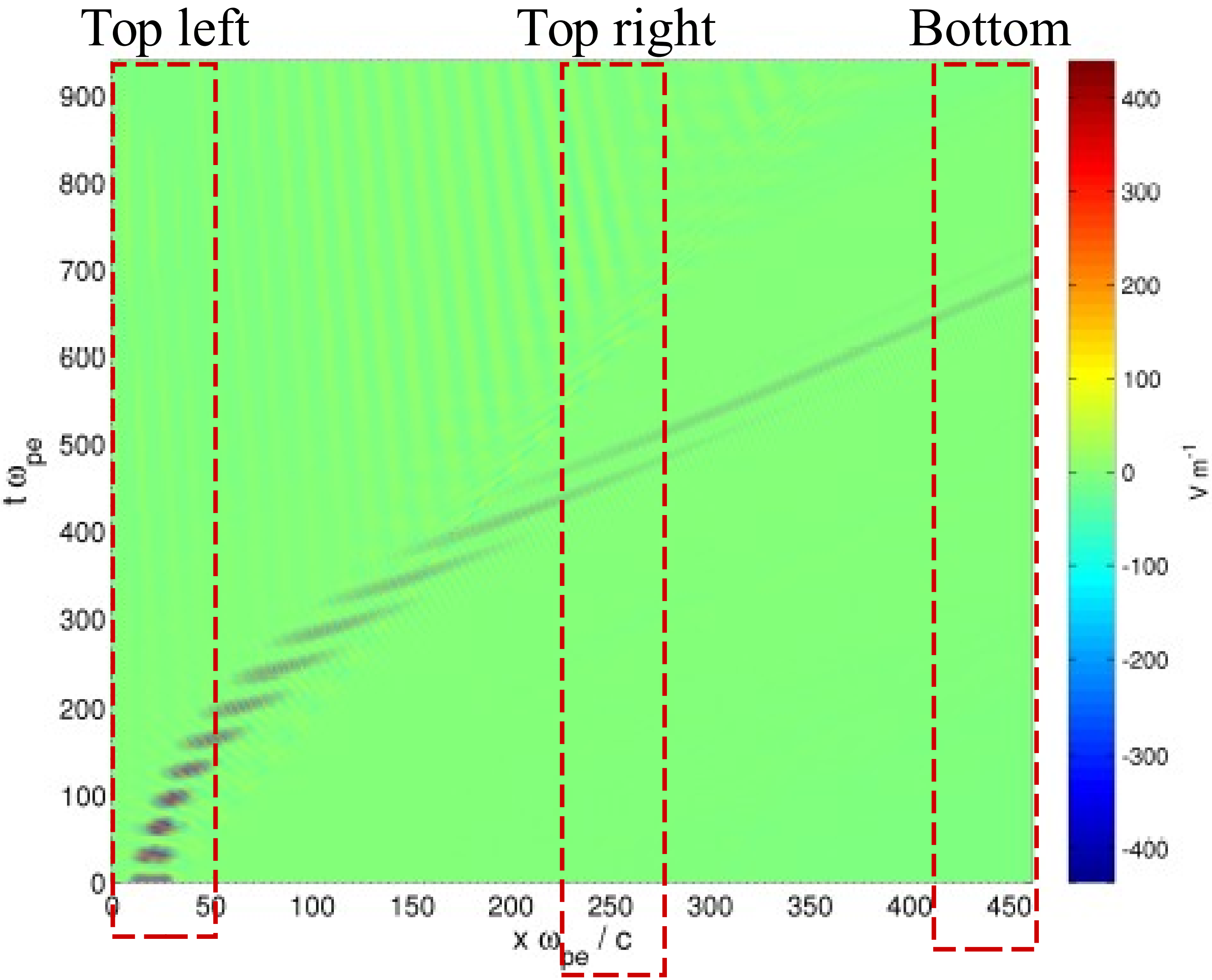
Non-gyrotropic beam
+density gradient=
EM emission

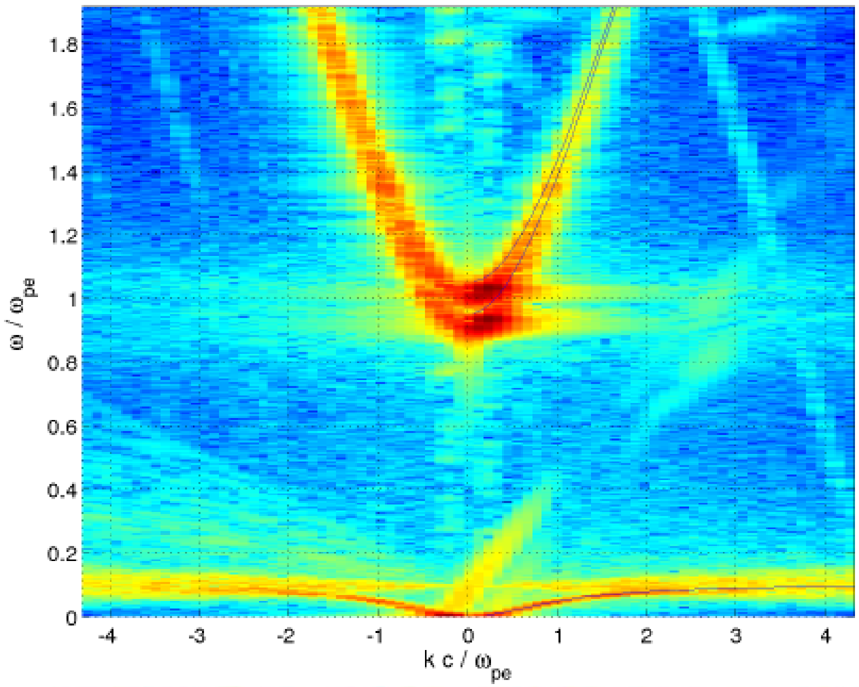
Gyrotropic beam=
No EM emission

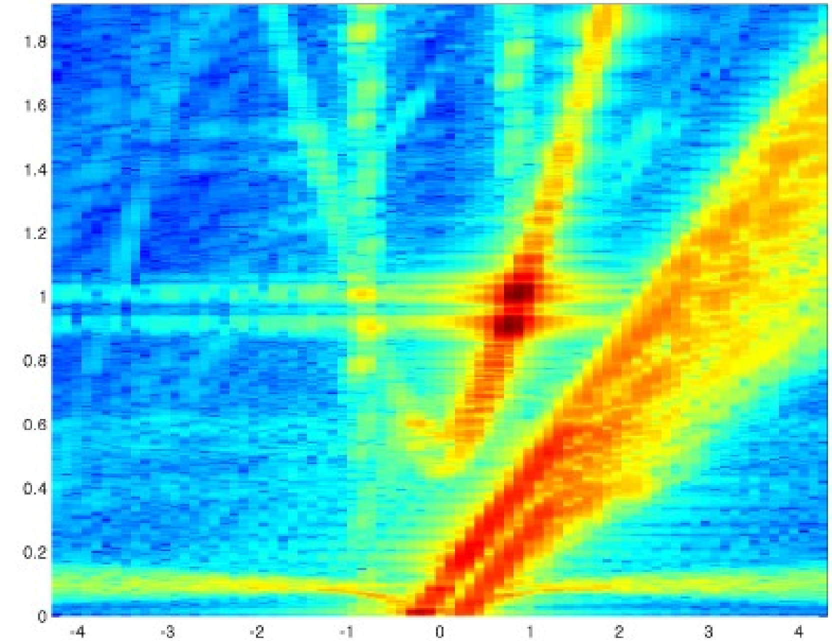


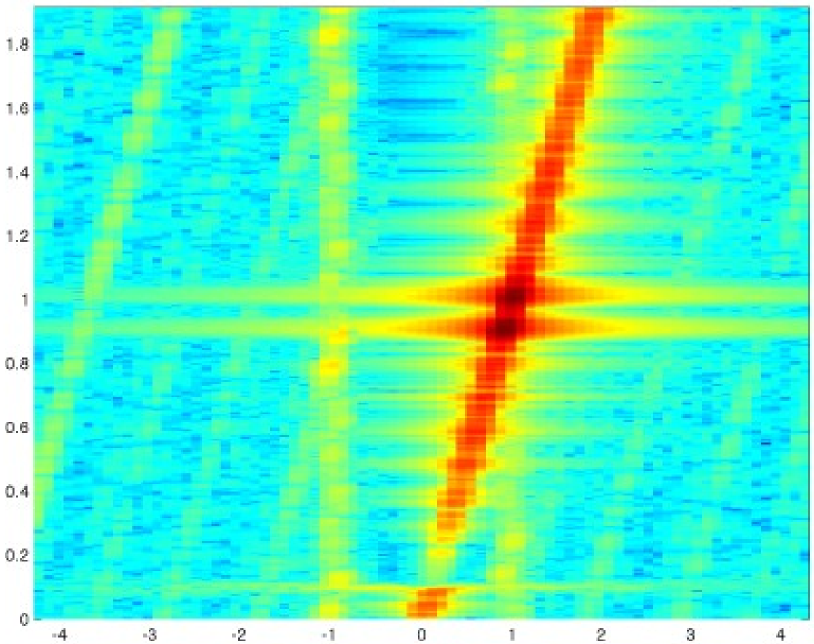
v_y-v_z phase space densities for the long reference run (left column) and ring distributed beam (right column) at
t=0 (top),
t=900 ω_{pe}^{-1}, (middle) and
t=1800 ω_{pe}^{-1}, (bottom).

Input for 2D Fourier transform of E_y on next slide









2D Fourier transform of E_y.
Top left -- beam injection region
Top right -- middle simulation box
Bottom -- the right edge of the box
for the reference run. **Conclusions: When non-gyrotropic beam is injected on a density gradient, escaping EM radiation is generated;**

Study 2

* J.O. Thurgood, D. Tsiklauri, "Self-consistent particle-in-cell simulations of fundamental and harmonic radio plasma emission mechanisms", Astron. Astrophys. 584, A83 (2015)

This study is motivated by three factors

(i) some PIC simulations studies use very large n_b/n_0=0.01-0.05 to computationally shorten quasilinear relaxation timescale

$$\tau_{\mathrm{ql}} = (n_0/n_\mathrm{b})\,(v_\mathrm{b}/\Delta v_\mathrm{b})^2\,\omega_{\mathrm{pe}}^{-1})$$

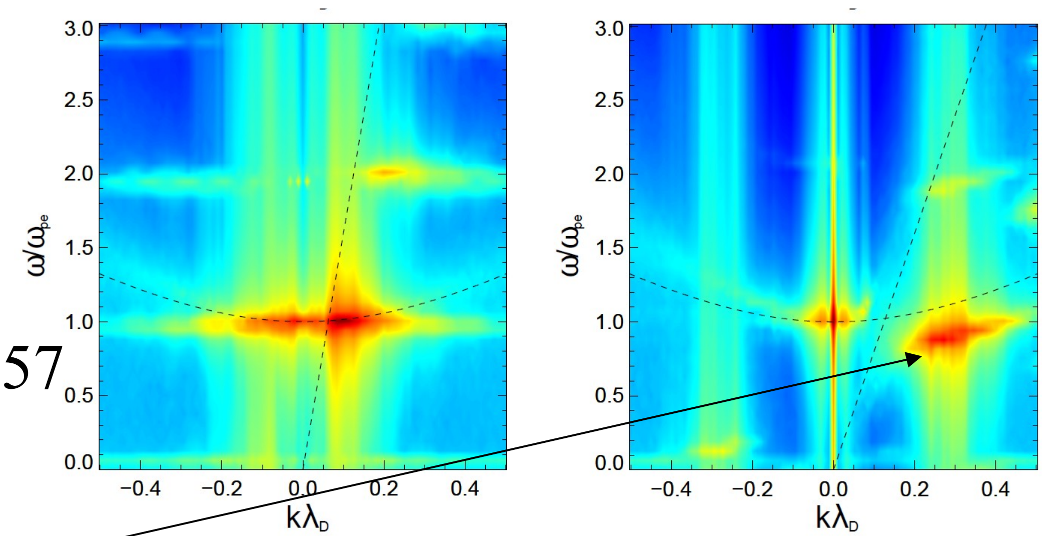
observational $n_b/n_0=10^{-5}$--10^{-7} !

(ii) Works such as Kasaba et al. (2001) are not reproducible;

(iii) Ganse et al. (2012b,a,2014), erroneously require the two beams, i.e. counter-propagating beams, for the emission mechanism to work.

The key point is that too dense beam prohibits ES decay

Run 1
dilute
beam
$n_b/n_0=0.0057$



Run 2
dense
Beam
$n_b/n_0=0.05$

$L \rightarrow L_1 \pm S$;

$0.9 \approx \omega_{L1}/\omega_{pe} \pm \omega_S/\omega_{pe}$;

$\omega_{L1}/\omega_{pe} > 1 \rightarrow \omega_S/\omega_{pe} > 0.1$ which is impossible because $\omega_{pi}/\omega_{pe} \approx 0.02$!

Inhibited ES decay means that no backwards propagating Langmuir wave is available to take part in the tree-wave interaction, i.e. no $2\omega_{pe}$ EM in Run 2.

J.O. Thurgood, D. Tsiklauri, Astron. Astrophys. 584, A83 (2015)

Study 3 (the main work presented here)

J.O. Thurgood, D. Tsiklauri, "Particle-in-cell simulations of the relaxation of electron beams in inhomogeneous solar wind plasmas", J. Plasma Phys. (2016), vol. 82, 905820604.

Key point is the electron beams observationally would relax too quickly.

Hence need some mechanism to stop this.

Inhomogeneity?

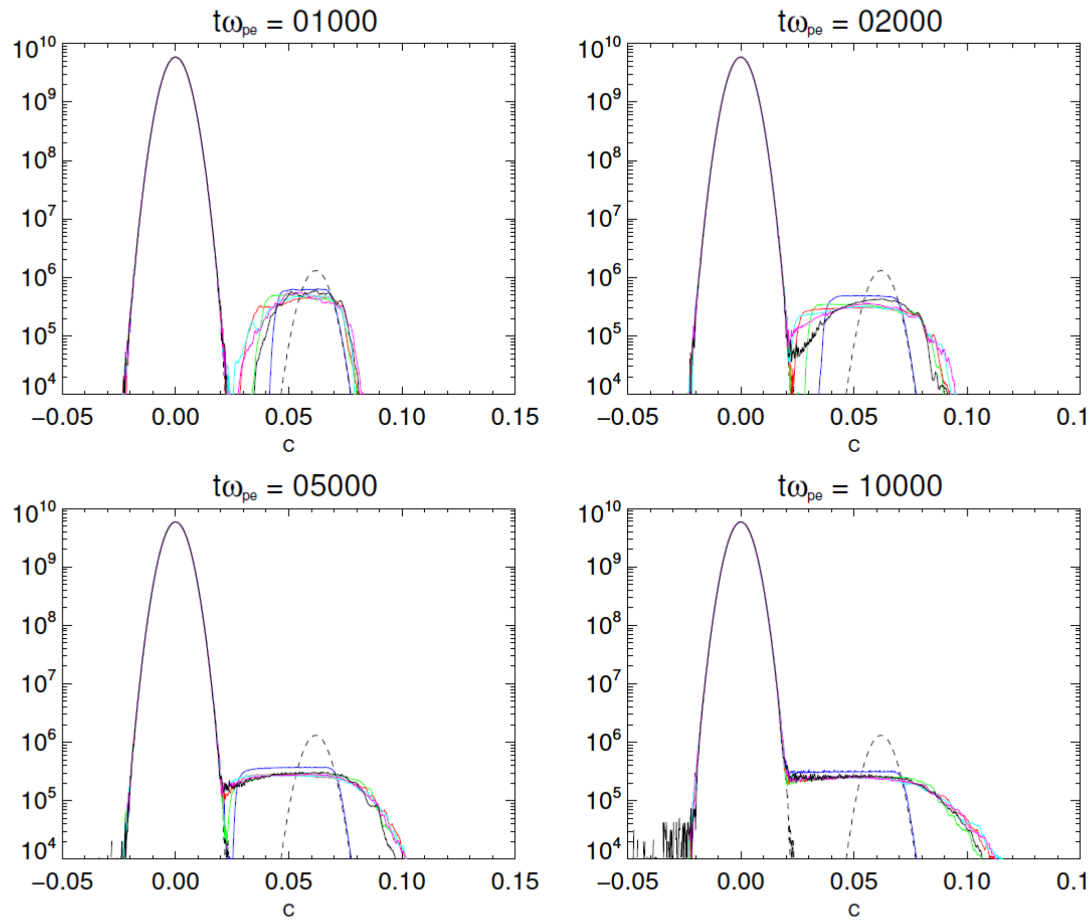
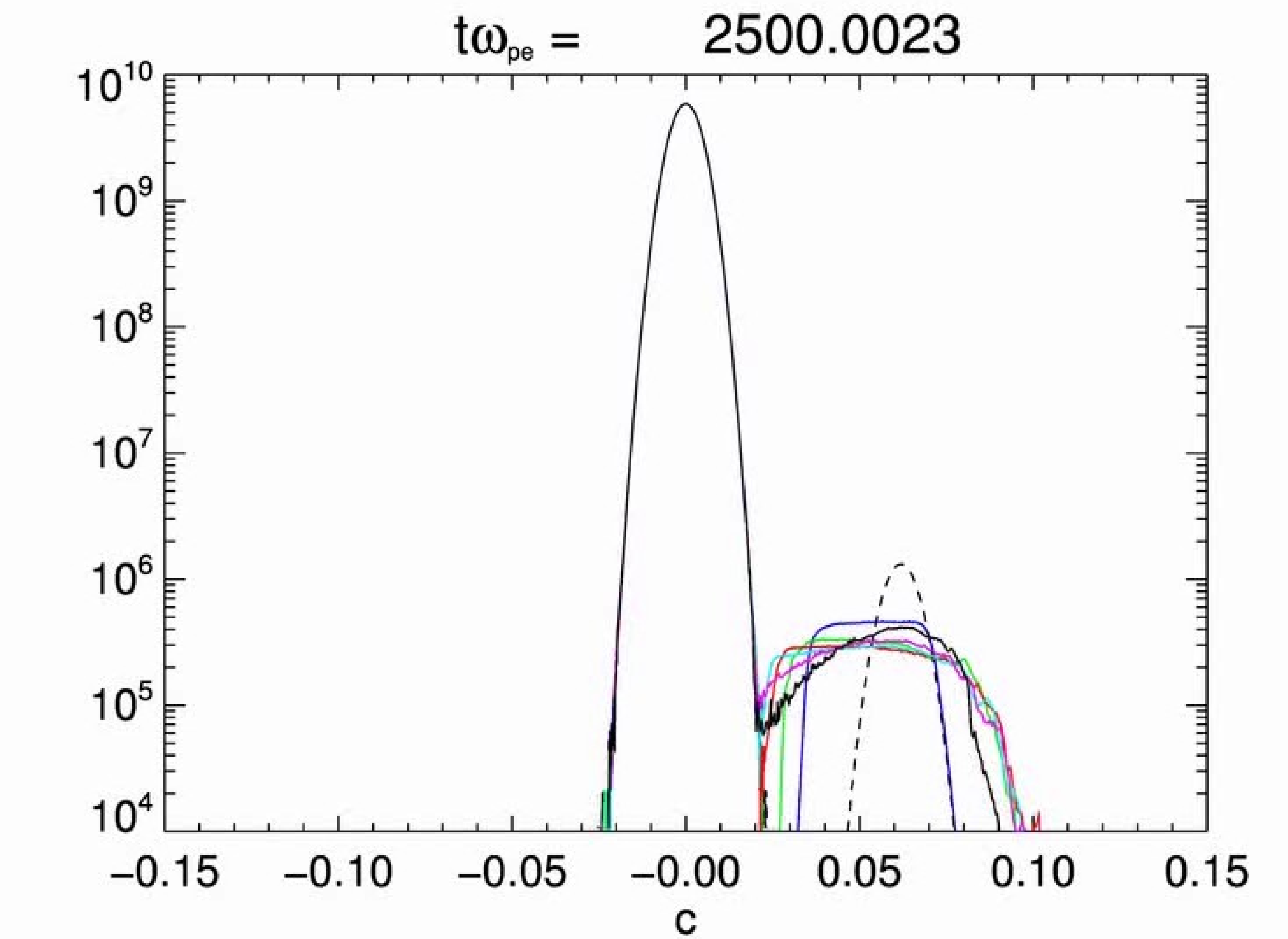


FIGURE 1. Influence of the level of inhomogeneity on the evolution of the electron velocity distribution function with time, where $\Delta n = 0$ (blue), 0.01 (green), 0.02 (red), 0.03 (cyan), 0.04 (magenta) and 0.05 (black). The initial profile of the electrons (common to all cases) is shown by the black dashed line. The full temporal evolution can be seen in the associated online movie.

blue homogenous other colours above the threshold and inhomogeneous



Dispersion relation for Langmuir waves $\omega^2 = \omega_{pe}^2 + 3V_{the,e}^2 k^2$

Dispersion relation for electron beam $\omega = V_b k$

in wave-particle resonance $\omega = \sqrt{\omega_{pe}^2 + 3V_{the,e}^2 k^2} = V_b k$

Following Ryutov (1969), the modified Langmuir wave dispersion relationship in the presence of such a density inhomogeneities is to the first order

$$\omega = \sqrt{\omega_{pe}^2 + 3V_{the,e}^2 k^2} \approx \omega_{pe}\left(1 + \frac{1}{2}\frac{\delta n}{n}\right) + \frac{3}{2}\frac{V_{the,e}^2 k^2}{\omega_{pe}}$$

Thus, the condition for density fluctuation to modify dispersion relat. is $\boxed{\frac{\delta n}{n} > \frac{3V_{the,e}^2 k^2}{\omega_{pe}^2}}$ or after putting in $k \approx \omega_{pe}/V_b$ $\boxed{\frac{\delta n}{n} > \frac{3V_{the,e}^2}{V_b^2}}$

blue homogenous
other colours above the threshold and inhomogeneous

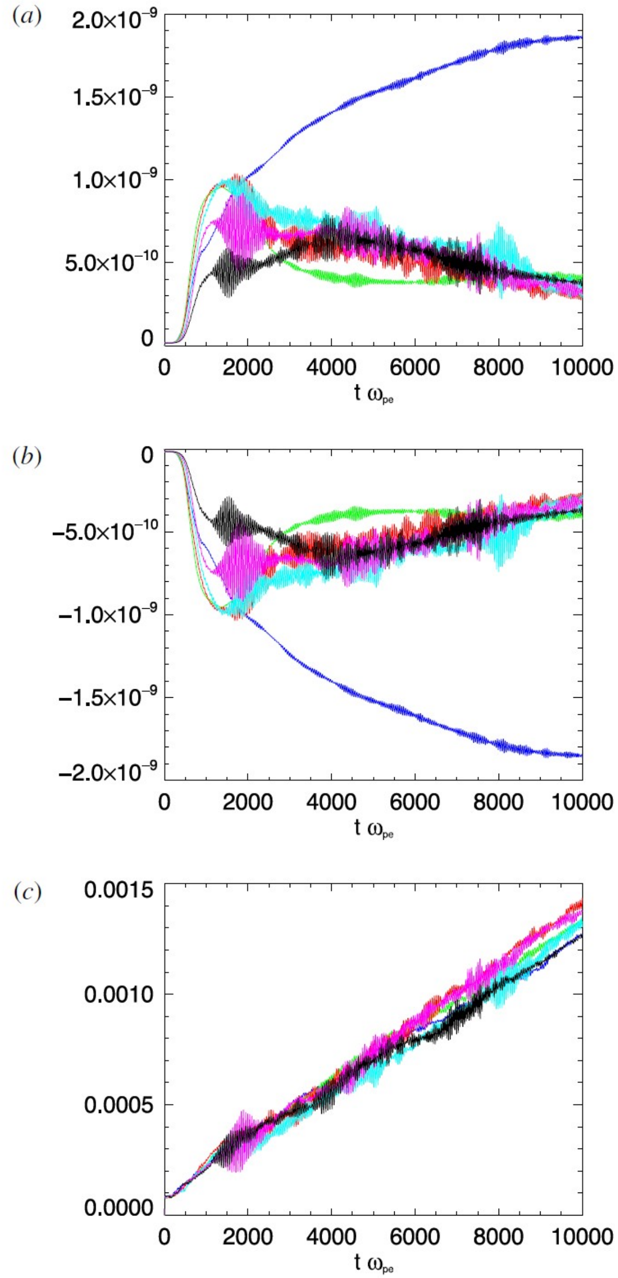
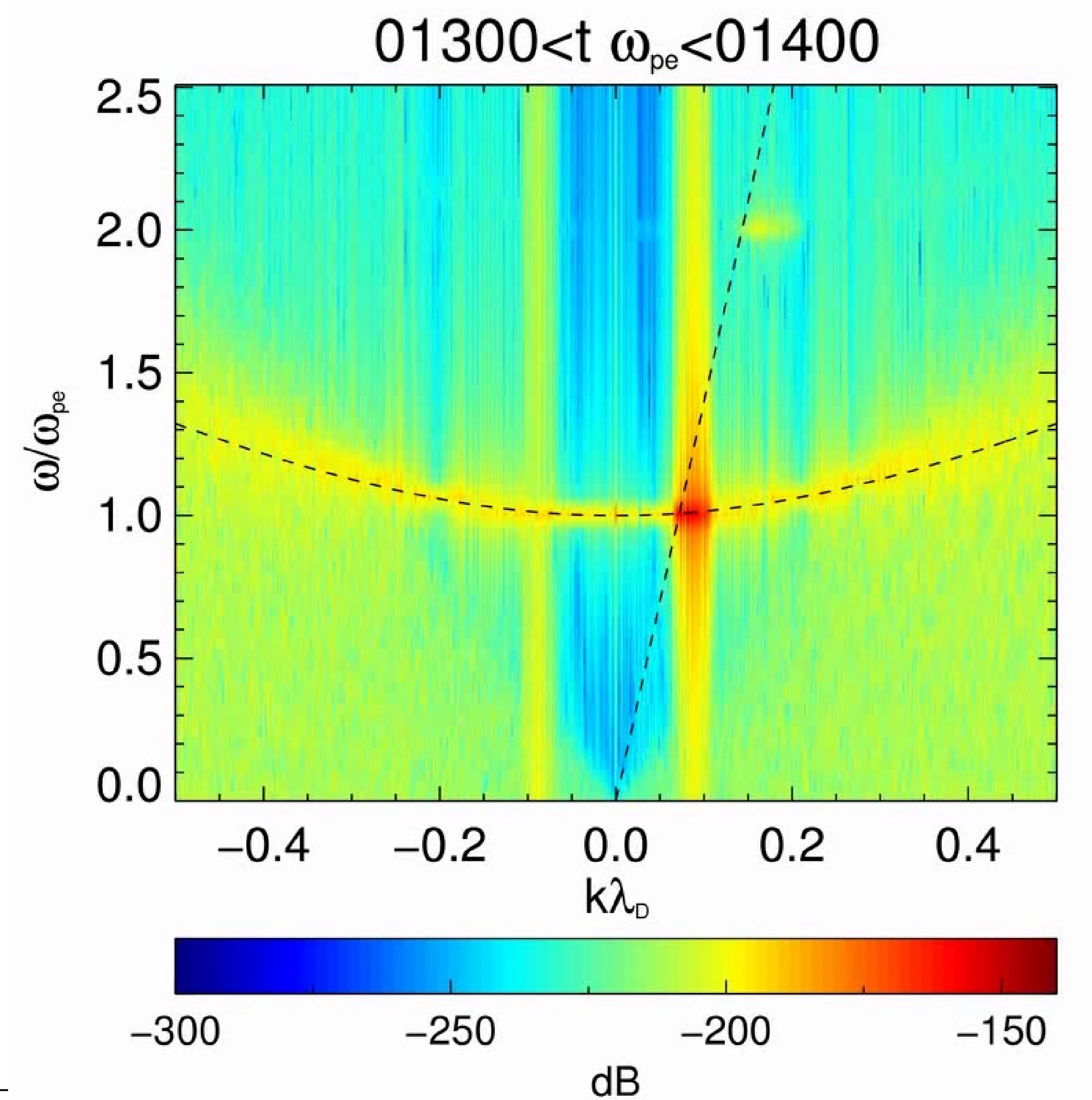


FIGURE 2. Evolution of (*a*) total field energy (*J*), (*b*) total particle energy (*J*), and (*c*) total simulation energy (% change) over time for the six runs of increasing inhomogeneity amplitude – $\Delta n = 0$ (blue), 0.01 (green), 0.02 (red), 0.03 (cyan), 0.04 (magenta) and 0.05 (black).

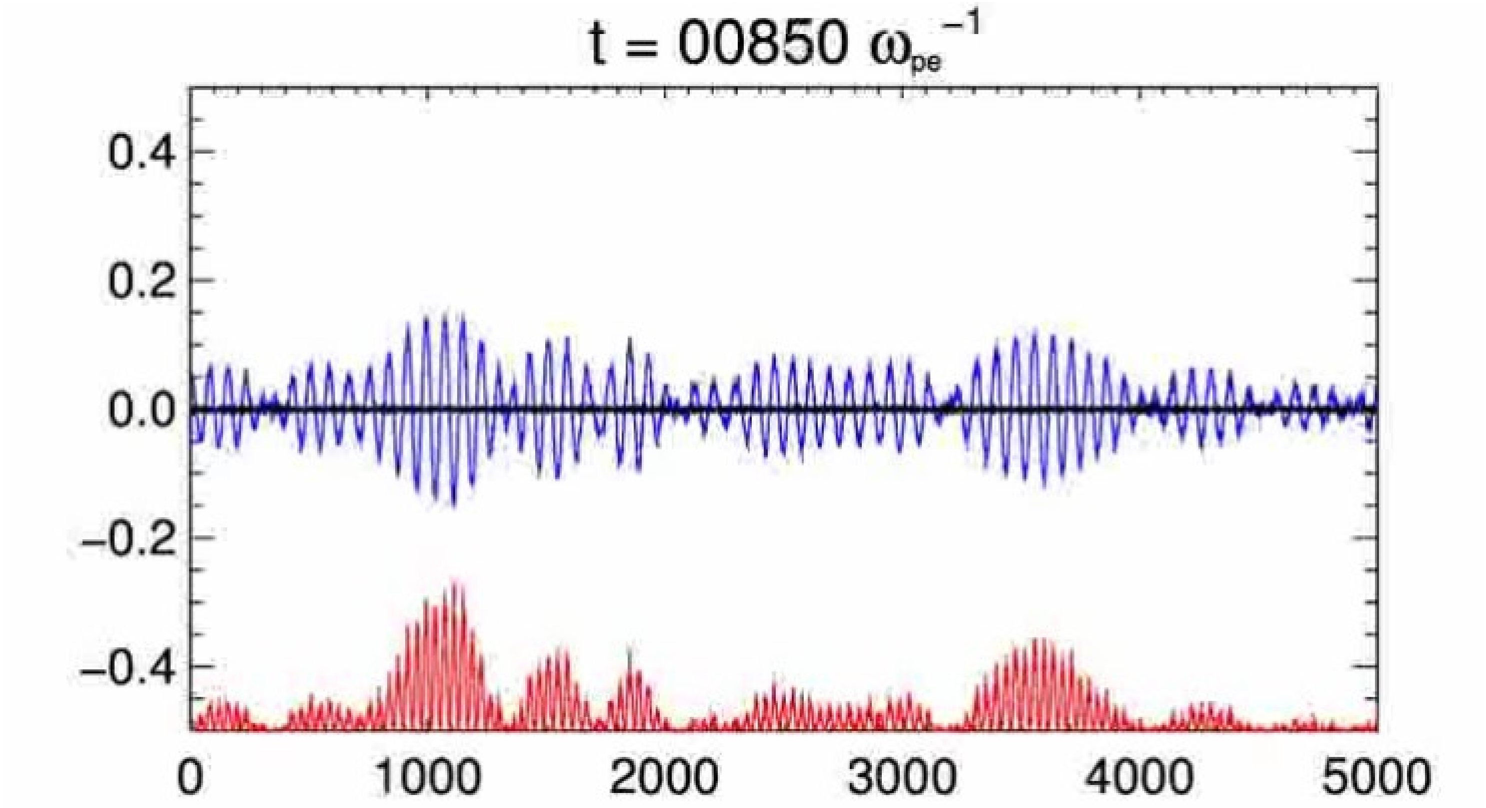
δn/n=0



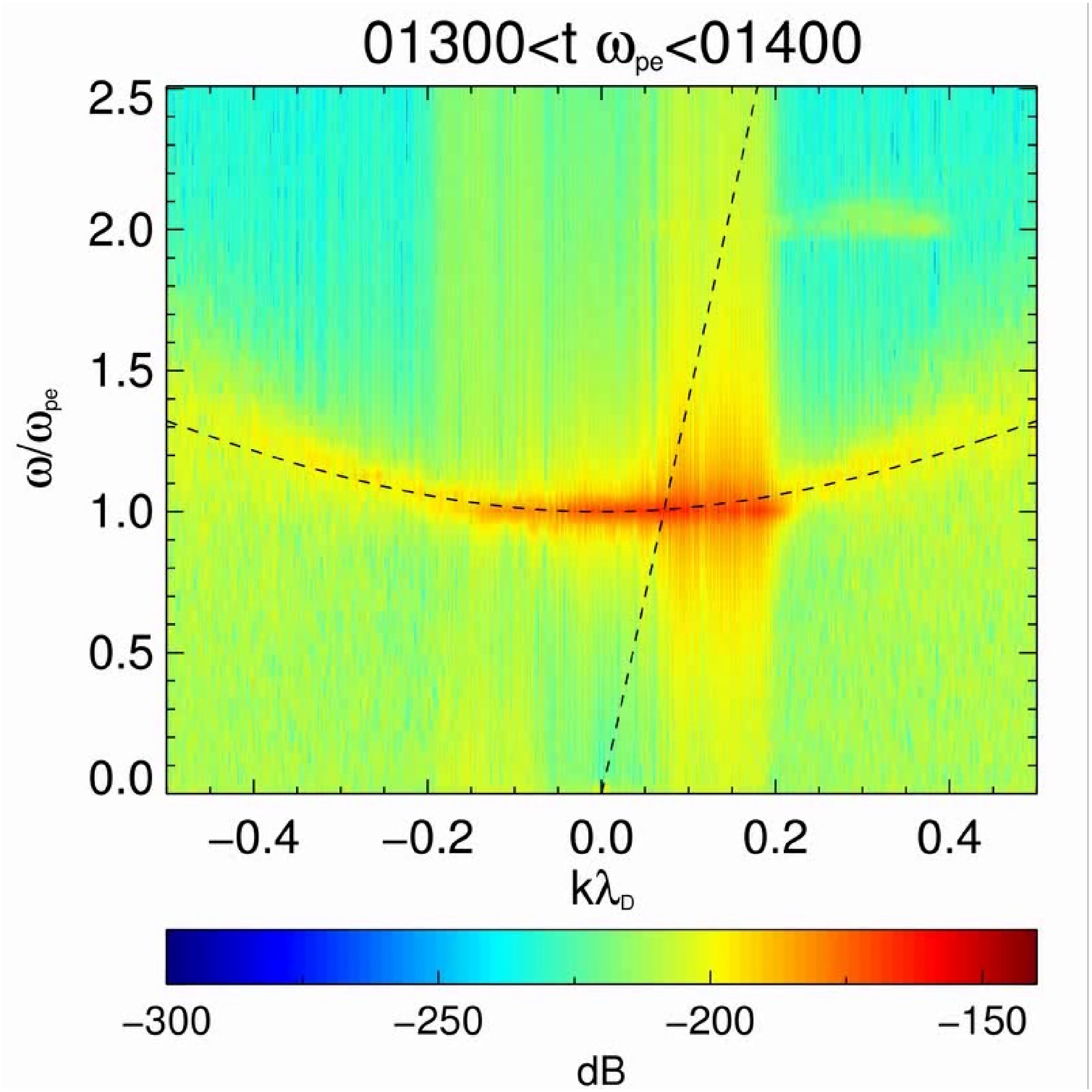
NOTE
how k
increases

$\delta n/n=0$

NO refraction -- just localization



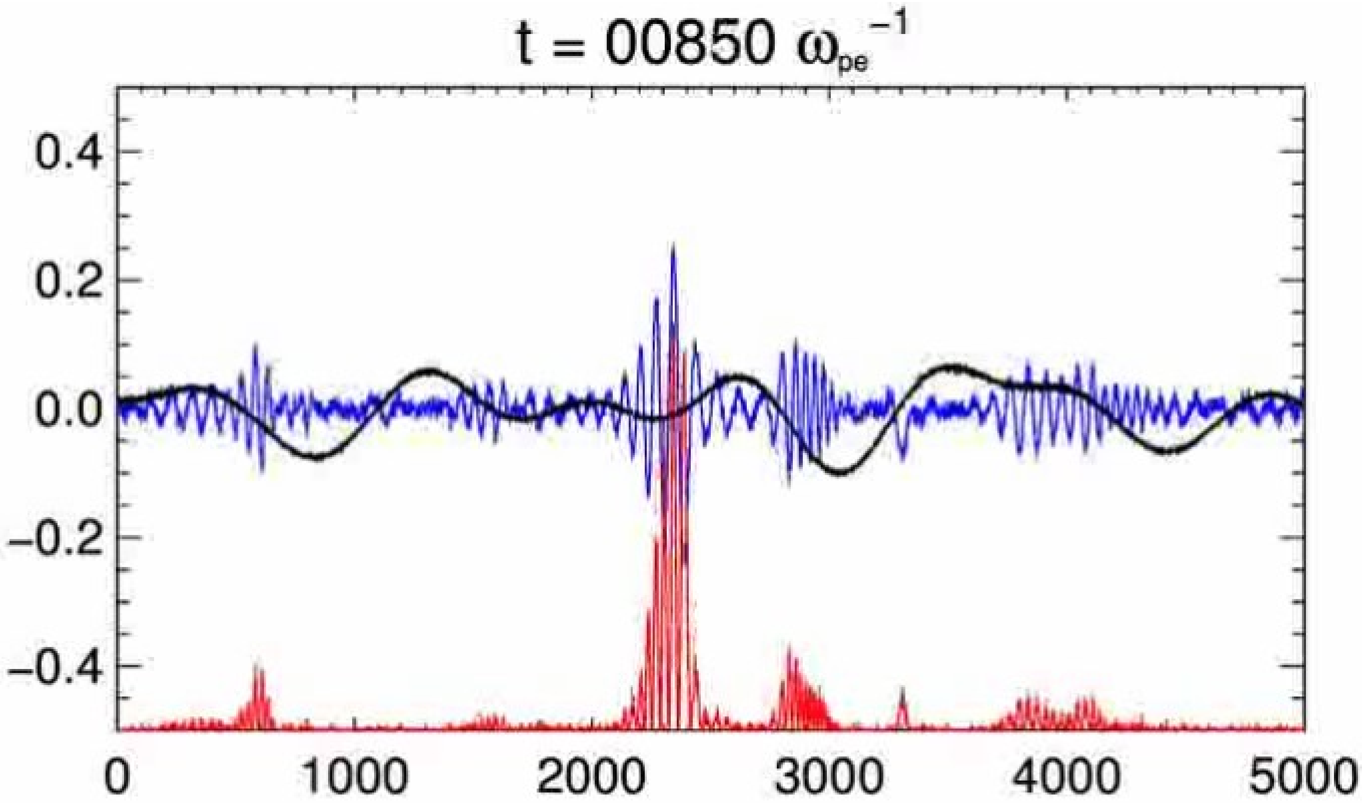
$\delta n/n$=0.05



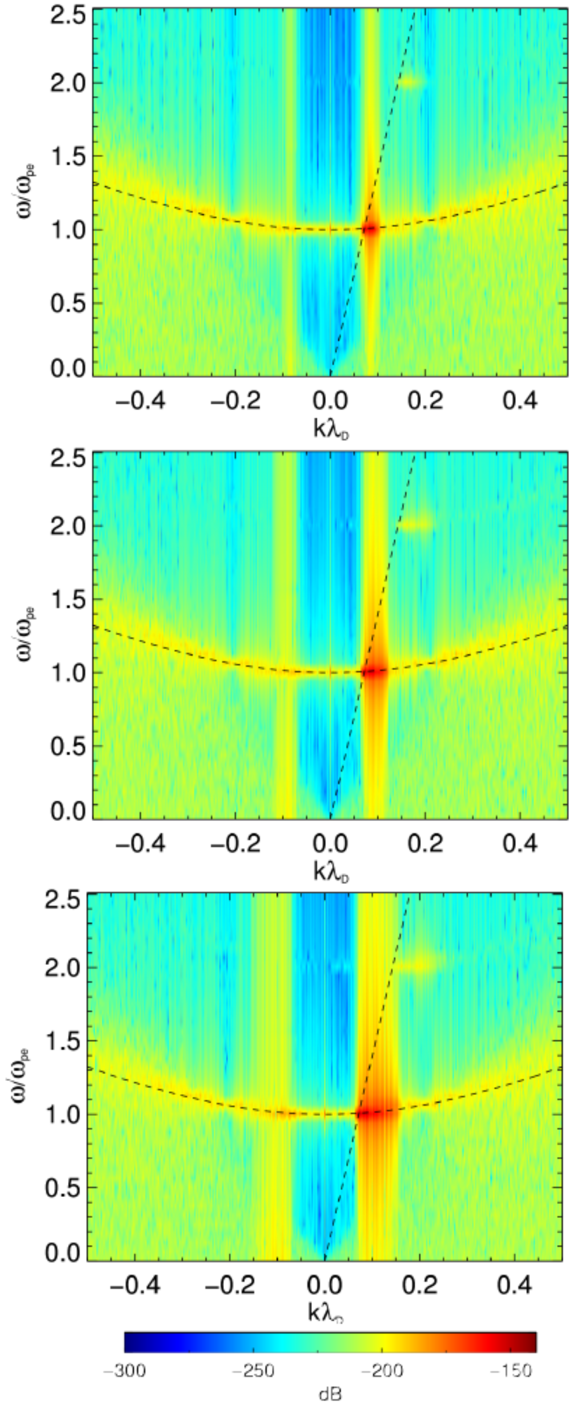
NOTE
how k
decreases including becoming <0

δn/n=0.05

A LOT of refraction AND localization



δn/n=0



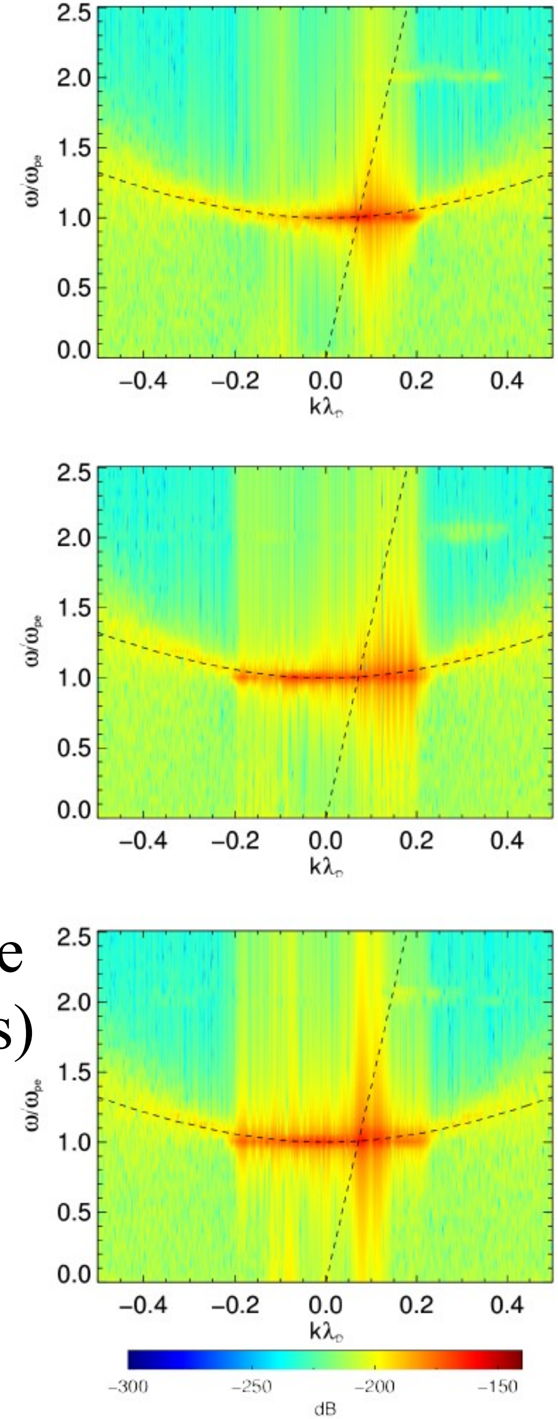
δn/n=0.05

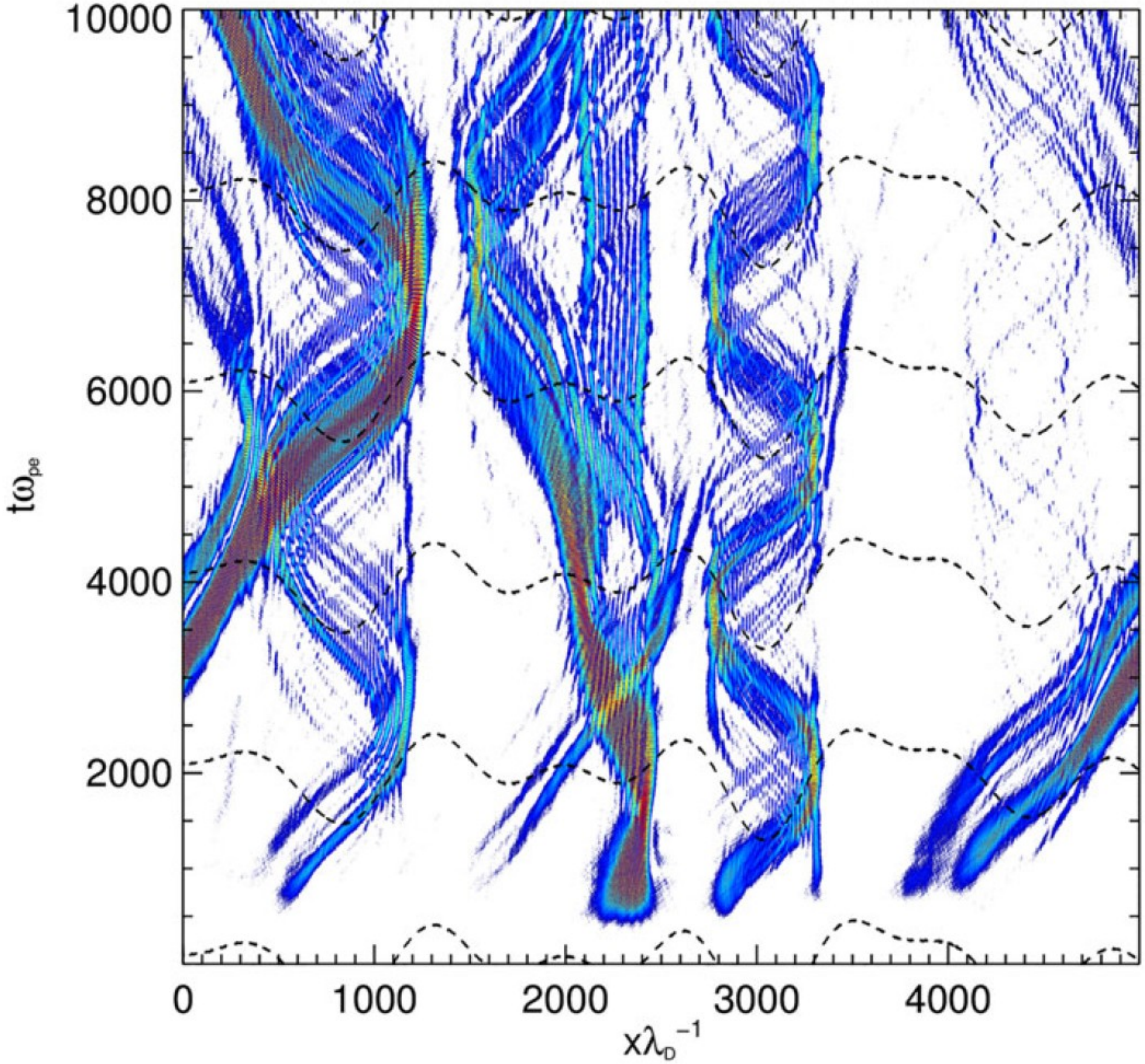
Conclusions:

inhomogeneity detunes wave-particle resonance

and

energy exchange (waves-particles) is hampered.





δn/n=0.05

FIGURE 11. Time–distance diagram of electric field energy for $\Delta n = 0.05$, illustrating the temporal evolution of the spatially localised wave packets. Note the reflections of the packets between the walls of the density cavities, where the black dashed lines illustrate the density profile along x. Levels of the colour table are logarithmically spaced, for best contrast between features (see figure 10 for corresponding quantitative information).

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As discussed by Pechhacker & Tsiklauri (2014), at positive density gradient locations *k* decreases, which means that Langmuir waves are resonant with higher-velocity electrons,
$V_{ph} = \omega_{Langmuir} / k$, hence we see particle acceleration in the inhomogeneous case, but no acceleration in the uniform density case.

The key point is that drift towards smaller *k*, including negative does not require three-wave interaction or ion-sound-mediated decay and naturally occurs due to wave refraction alone.
(1) Negative density gradients and
(2) quasi-linear relaxation both lead to increase in *k*, but do not result in the particle acceleration.

Thus the inhomogeneity detunes wave-particle resonance and energy exchange (waves-particles) is hampered.