Fundamental and harmonic electromagnetic emissions in solar wind plasmas with density fluctuations : 2D PIC simulations

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OBJECTIVES

The aim is, in solar wind conditions relevant to Type III solar radio bursts, to study the impact of random density fluctuations of the background plasma on the electromagnetic wave radiation at frequencies ω_p and $2\omega_p$.

Mechanisms of waves' transformations on the inhomogeneities (scattering, refraction, reflection, conversion, tunneling, trapping, localization or/and diffusion...) lead to the transport of wave energy toward larger/smaller wavevector scales and thus modify the spectra of the Langmuir wave turbulence and its subsequent EM wave emissions.

MODEL AND PARAMETERS (1)

Simulations are performed :

- with the 2D3V version of the open source relativistic full PIC code SMILEI (Derouillat, J., Beck, A., Perez, F. et al. 2018, Comput. Phys. Commun. 222, 351-373).

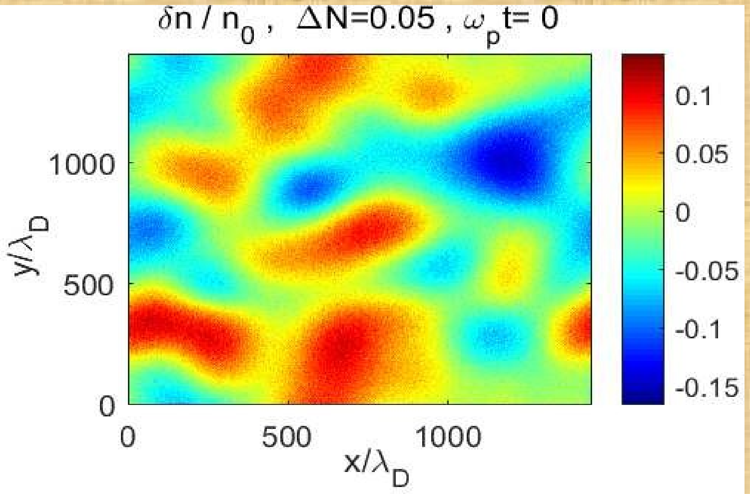
Two boxes are used :

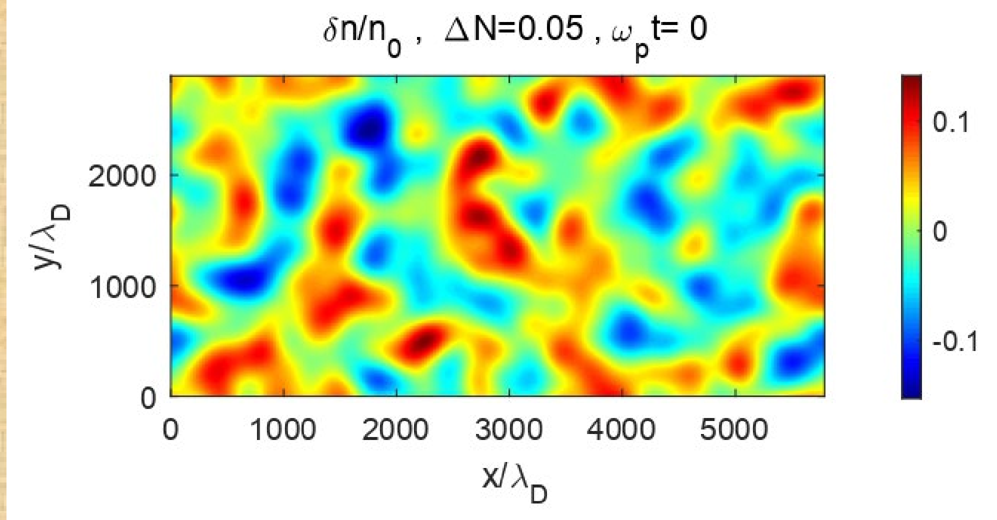
- "small" box : $N_x \times N_y = 1024 \times 1024$, $L_x \times L_y = 1448 \times 1448\lambda_D^2$. The resolution is $\delta k_{x,y}\lambda_D = 0.0043$ (along each direction), to compare with the theoretical wavevectors' moduli of the electromagnetic waves emitted at frequency $2\omega_p$, i.e. $k\lambda_D = \sqrt{3}v_T/c \simeq 0.048$.

- "larger" box : $N_x \times N_y = 4096 \times 2048$, $L_x \times L_y = 2896 \times 5792\lambda_D^2$. The resolutions are $\delta k_x\lambda_D = 0.001$ and $\delta k_y\lambda_D = 0.002$, to compare with the theoretical wavevectors' moduli $k_{th}\lambda_D = \sqrt{3}\,(k_L\lambda_D)\,v_T/c \simeq 0.004$ of the electromagnetic waves emitted at ω_p through nonlinear wave processes; k_L is the characteristic wavevector of the Langmuir waves.

MODEL AND PARAMETERS (2)

- The background plasma is initiated without or with random density fluctuations δn of average level $\Delta N = \langle(\delta n/n_0)^2\rangle^{1/2} = 0.05$ $(0 < \Delta N \lesssim 0.07)$ and wavelengths much larger than the Langmuir waves' ones. Variability : $|\delta n/n_0|$ can reach locally around 0.15.





Size of boxes : $L_x=L_y=1448\lambda_D$ (left) and $L_x=5792\lambda_D$, $L_y= 2896\lambda_D$ (right)

- Three species are used : plasma electrons, plasma ions, beam electrons : 1800 particles per cell and per species $\longrightarrow$ 5.6 10^9 particles in the"small" box and 4.5 10^{10} in the "larger" box $\longrightarrow$ Reduction of the numerical noise below 10^{-2}, i.e. significantly below ΔN.

MODEL AND PARAMETERS (3)

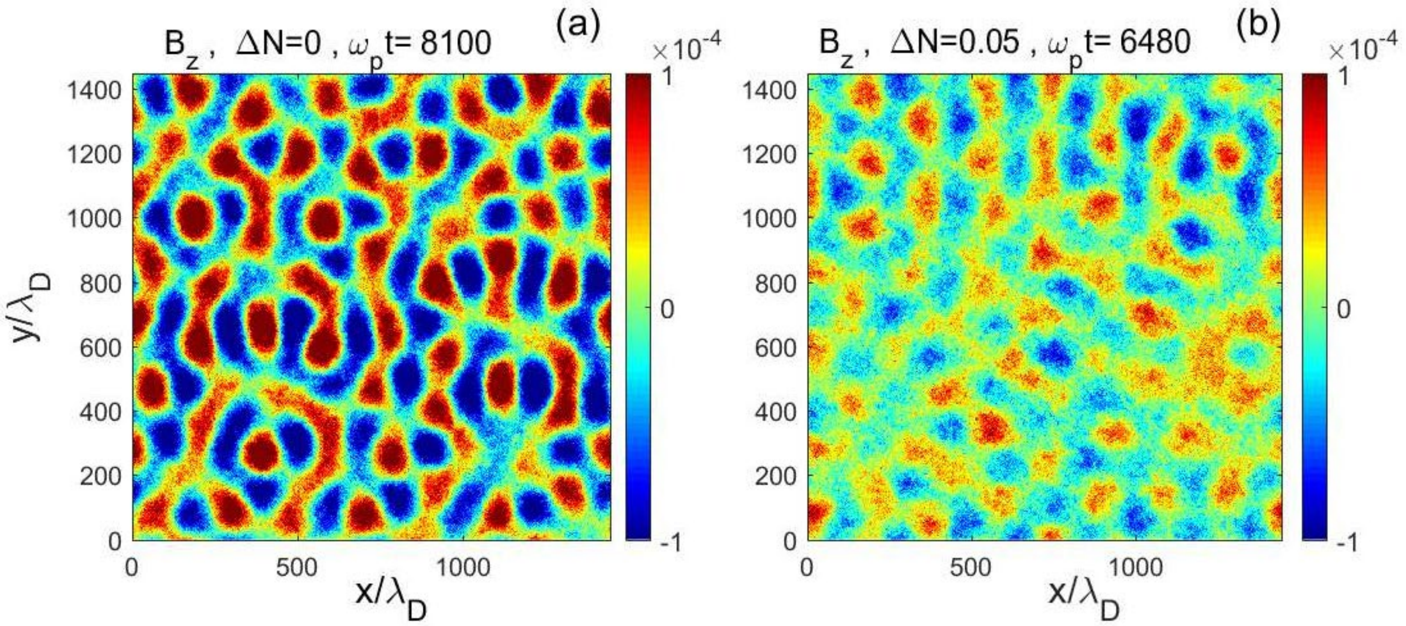
Physical parameters used are typical of Type III solar radio bursts regions in weakly magnetized solar wind and coronal plasmas.

- Beam density : $n_b = 5\ 10^{-4}\ n_0$
- Beam drift velocity along the x-axis : $v_b = 9v_T$, with a thermal velocity $v_{T_b} = v_T = 0.028c$ ($v_b = 0.25c$).
- Background plasma temperatures : $T_i/T_e = 0.1$

- Realistic mass ratio $m_p/m_e = 1836$
- Selfconsistent calculations
- Variation of the total energy less than 2×10^{-4} over roughly 10^6 time steps
- Turbulence parameter below 10^{-2} : no ponderomotive effects
- Several thousands of plasma periods (up to $\omega_p t \simeq 8100$) are necessary to follow the full dynamics of such weak beams and the subsequent generation of the electromagnetic wave emissions.

HARMONIC ELECTROMAGNETIC EMISSIONS AT FREQUENCY $2\omega_p$

RADIATED MAGNETIC FIELD $B_z(x,y)$

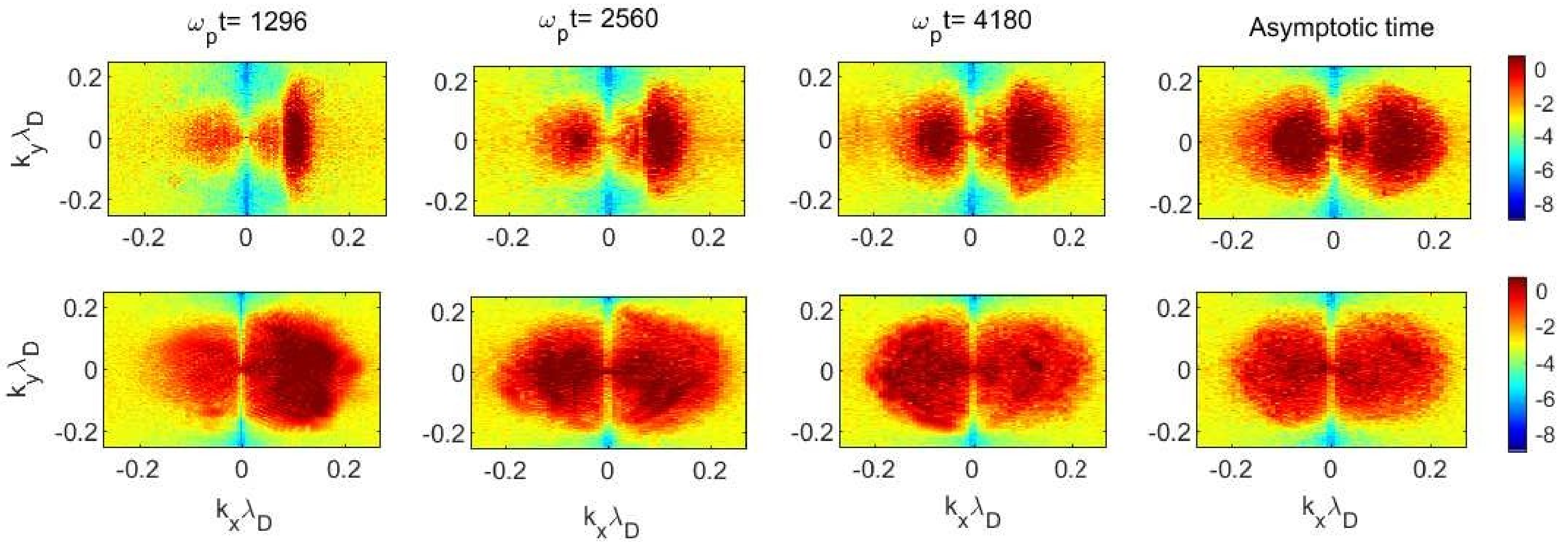


Spatial distributions of the magnetic field component $B_z(x,y)$ at asymptotic times, when (a) the plasma is homogeneous (i.e. $\delta n(x,y)=0$ and $\Delta N=0$) and (b) when it is initially randomly inhomogeneous, with $\Delta N=0.05$.

- EM waves propagating obliquely
- Wavelengths in agreement with the theoretical estimation of $k_{\mathcal{H}}\lambda_D \simeq 0.04$
- $\mathbf{k}_{\mathcal{H}}$: wavevector of EM waves $\mathcal{H}$ emitted at $2\omega_p$ via the coalescence $\mathcal{L}+\mathcal{L}' \to \mathcal{H}$ of beam-driven $\mathcal{L}$ and backscattered $\mathcal{L}'$ Langmuir waves.

Krafft and Savoini, ApJL, 917:L23, 2021

LANGMUIR WAVE SPECTRA AT ω_p



Distributions in the (k_x, k_y)-space of the normalized electric wave spectral energy density $\log_{10}|E_{xk}|^2$ emitted at the frequency $\omega_k \simeq \omega_p$, for $\Delta N = 0$ (upper row) and $\Delta N = 0.05$ (bottom row).

- Excitation of beam-driven $\mathcal{L}$ and backscattered $\mathcal{L}'$ Langmuir waves
- $\Delta N = 0$: spectral broadening due to beam relaxation $\longrightarrow$ energy transfer to larger k
- $\Delta N = 0$: waves $\mathcal{L}'$ mainly result from the ES 3-waves' decay $\mathcal{L} \rightarrow \mathcal{L}' + \mathcal{S}$ ($\mathcal{S}$: ion acoustic waves)
- $\Delta N = 0.05$: spectral broadening (wave scattering on δn +beam relaxation) occurs earlier and stronger, even before wave saturation
- $\Delta N = 0.05$: Langmuir waves' transformations on density fluctuations $\longrightarrow$ $\mathcal{L}'$ waves enhancement

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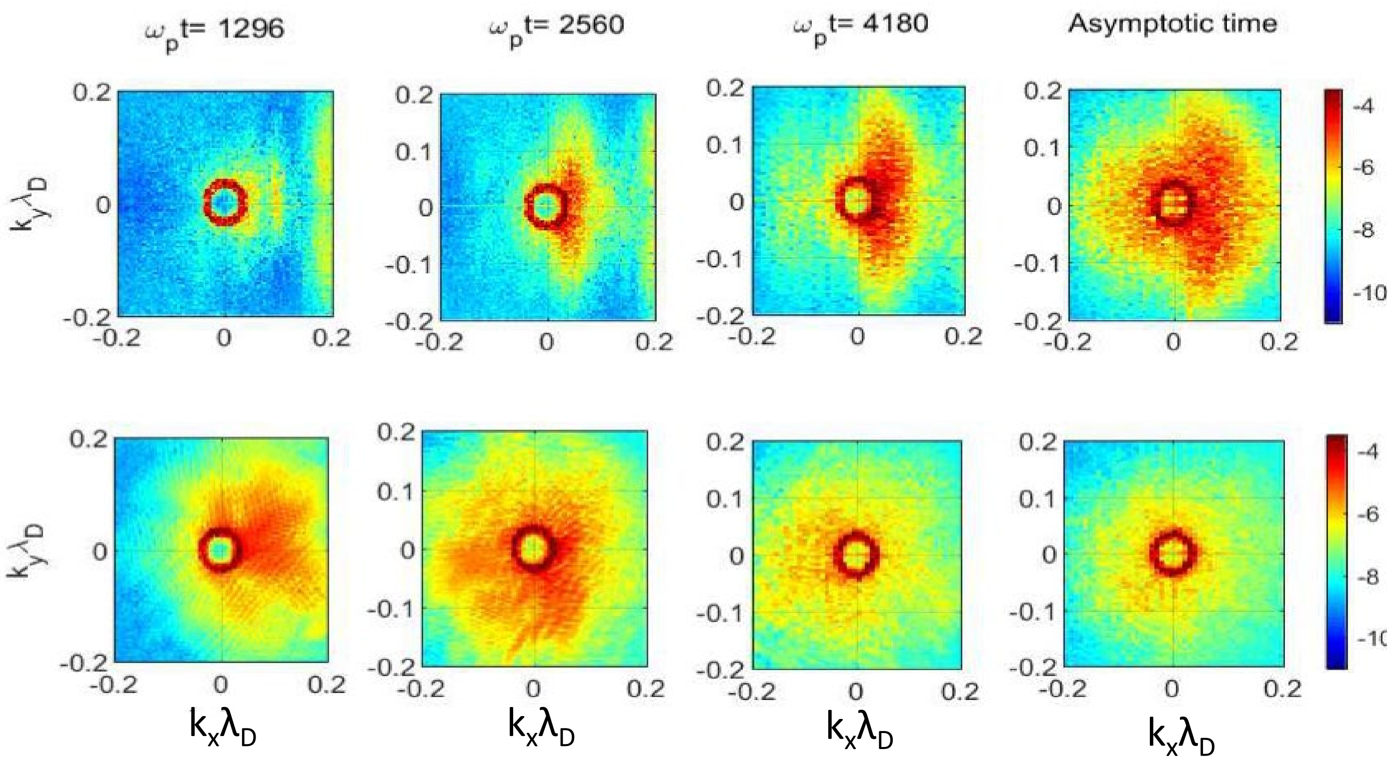
MAGNETIC FIELD SPECTRA

$B_{zk}^2(k_x,k_y)$



Distributions of the normalized magnetic wave spectral energy densities $\log_{10}(|B_{zk}|^2)$ emitted at the harmonic frequency $\omega_k \simeq 2\omega_p$, for $\Delta N = 0$ (upper row) and $\Delta N = 0.05$ (bottom row). The times of each column are the same as in previous figure.

- ▶ Circular structure of radius $k\lambda_D \simeq \sqrt{3}v_T/c$ corresponding to the dispersion of $\mathcal{H}$ waves
- ▶ $\Delta N = 0$: quadrupolar-type emission predicted by the theory.
- ▶ $\Delta N = 0.05$: scattered spectra with isotropization asymptotically
- ▶ Correspondance with Langmuir spectra via the resonant conditions $k_{\mathcal{H}x} = k_{\mathcal{L}x} + k_{\mathcal{L}'x} = k_{\mathcal{L}x} - |k_{\mathcal{L}'x}|$ of the coalescence process $\mathcal{L} + \mathcal{L}' \to \mathcal{H}$

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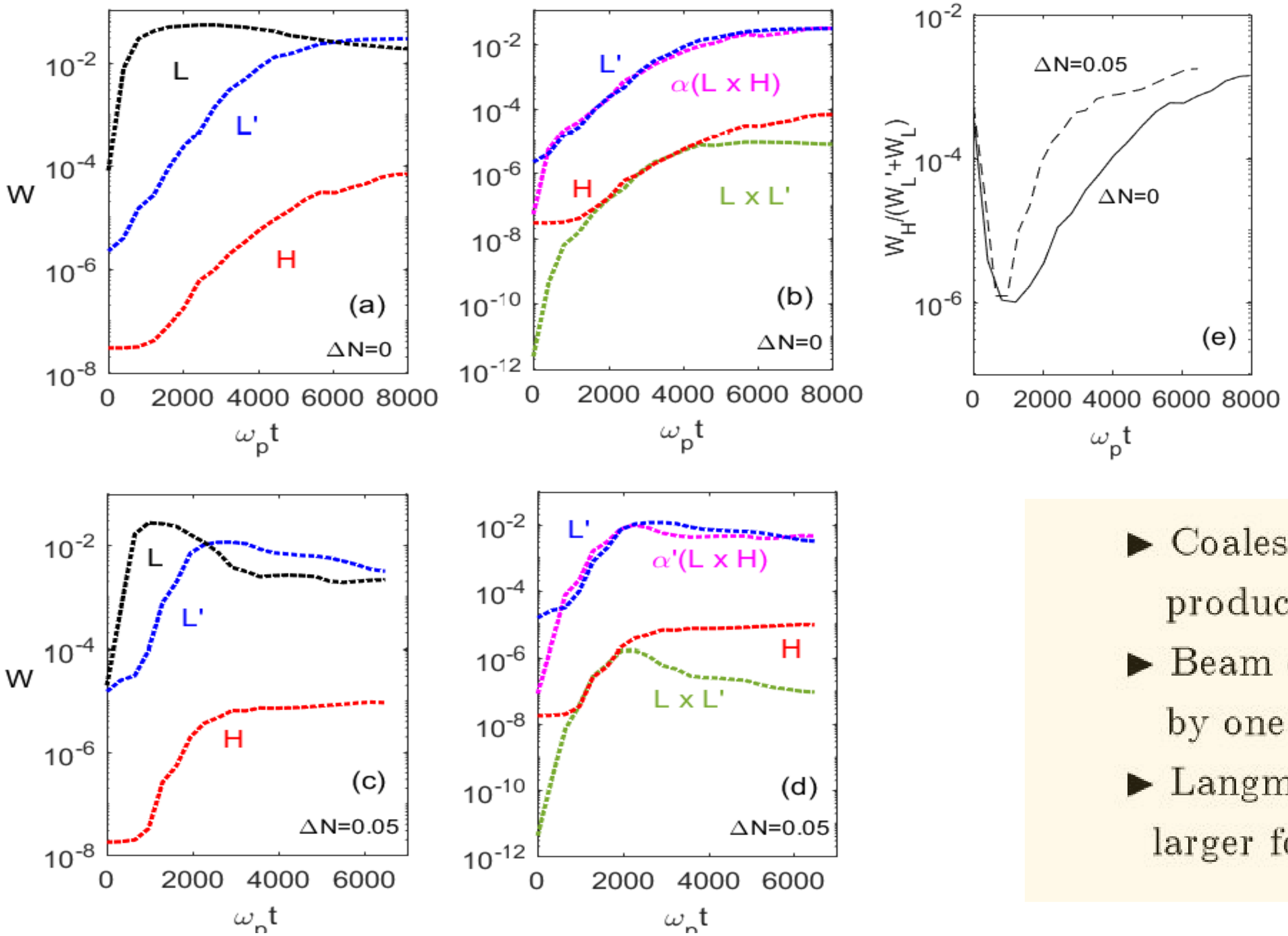
TIME VARIATIONS OF ENERGIES



- ▶ Coalescence of Langmuir waves' $\mathcal{L} + \mathcal{L}' \to \mathcal{H}$ produces $\mathcal{H}$ waves at $2\omega_p$ for $\Delta N = 0.05$
- ▶ Beam energy transfer to $\mathcal{H}$ waves : larger for $\Delta N = 0$ ($\sim 10^{-4}$) by one order of magnitude compared to $\Delta N = 0.05$
- ▶ Langmuir wave turbulence energy transfer to $\mathcal{H}$ waves : larger for $\Delta N = 0.05$ ($\gtrsim 10^{-3}$) compared to $\Delta N = 0$

(a-b) : homogeneous plasma ($\Delta N = 0$) ; (c-d) : plasma with density fluctuations ($\Delta N = 0.05$). (First column) : Variations with $\omega_p t$ of the energies $W_{\mathcal{L}}$ and $W_{\mathcal{L}'}$ carried by the beam-driven Langmuir waves $\mathcal{L}$, by the backscattered Langmuir waves $\mathcal{L}'$ at ω_p, and of the energy $W_{\mathcal{H}}$ carried by the electromagnetic waves $\mathcal{H}$ of frequency $2\omega_p$. (Second column) : Variations with $\omega_p t$ of (i) the energy $W_{\mathcal{H}}$ and the product $W_{\mathcal{L}} W_{\mathcal{L}'}$, and of (ii) the energy $W_{\mathcal{L}'}$ and the product $\alpha W_{\mathcal{L}} W_{\mathcal{H}}$. (e) : Time variation of $W_{\mathcal{H}}/(W_{\mathcal{L}} + W_{\mathcal{L}'})$ for $\Delta N = 0$ and $\Delta N = 0.05$. The energies are normalized by the initial beam kinetic energy.

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CONCLUSION : HARMONIC EM EMISSION

(i) The beam radiates $\mathcal{H}$ waves as a result of nonlinear processes of Langmuir waves' coalescence $\mathcal{L}+\mathcal{L}' \rightarrow \mathcal{H}$, despite the presence of linear phenomena of waves' scattering and transformations on the density fluctuations that strongly affect the Langmuir wave spectra.

(ii) The fraction of initial beam energy transferred asymptotically to $\mathcal{H}$ waves, of the order of 10^{-4} for the homogeneous plasma, and 10^{-5} for a inhomogeneous plasma with $\Delta N = 0.05$;

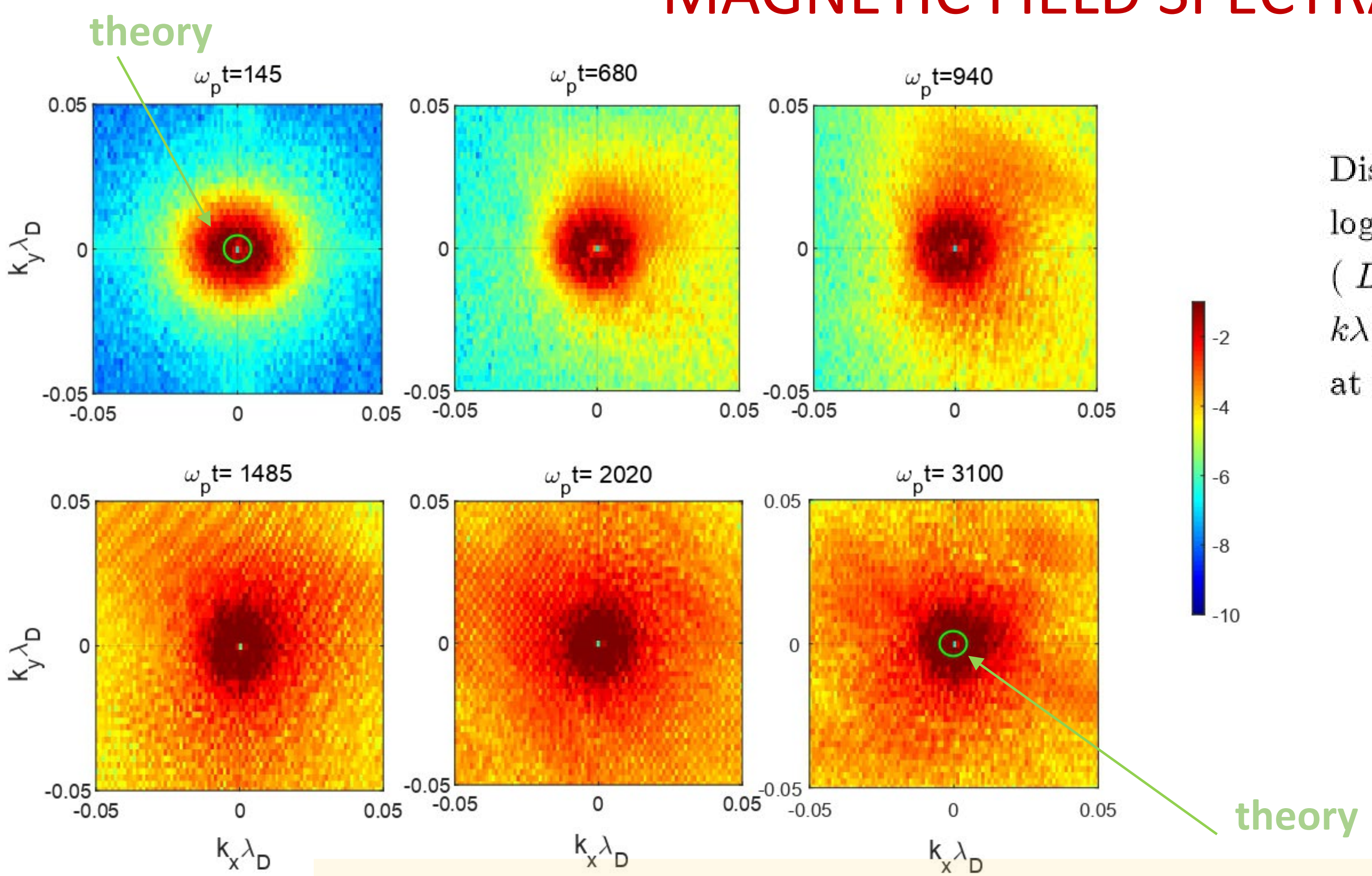
(iii) In a plasma with density fluctuations, the fraction of Langmuir wave energy transfered to $\mathcal{H}$ emissions is $\sim 10^{-3}$, larger during all the nonlinear stage than in a homogeneous plasma.

(iv) Backscattered Langmuir waves $\mathcal{L}'$ are produced at early times due to linear interaction phenomena of waves with density fluctuations, so that beam-driven Langmuir waves $\mathcal{L}$ do not need to reach sufficiently large amplitudes to produce them by nonlinear decay : $\mathcal{H}$ emissions production by coalescence of Langmuir wave turbulence is enhanced.

(v) Asymptotically, when the plasma is inhomogeneous, $\mathcal{H}$ emissions present isotropized spectra whereas quadrupolar radiation occurs for the homogeneous plasma case.

FUNDAMENTAL ELECTROMAGNETIC EMISSIONS AT FREQUENCY ω_p

MAGNETIC FIELD SPECTRA $B_{zk}^2(k_x,k_y)$ for ΔN=0.05



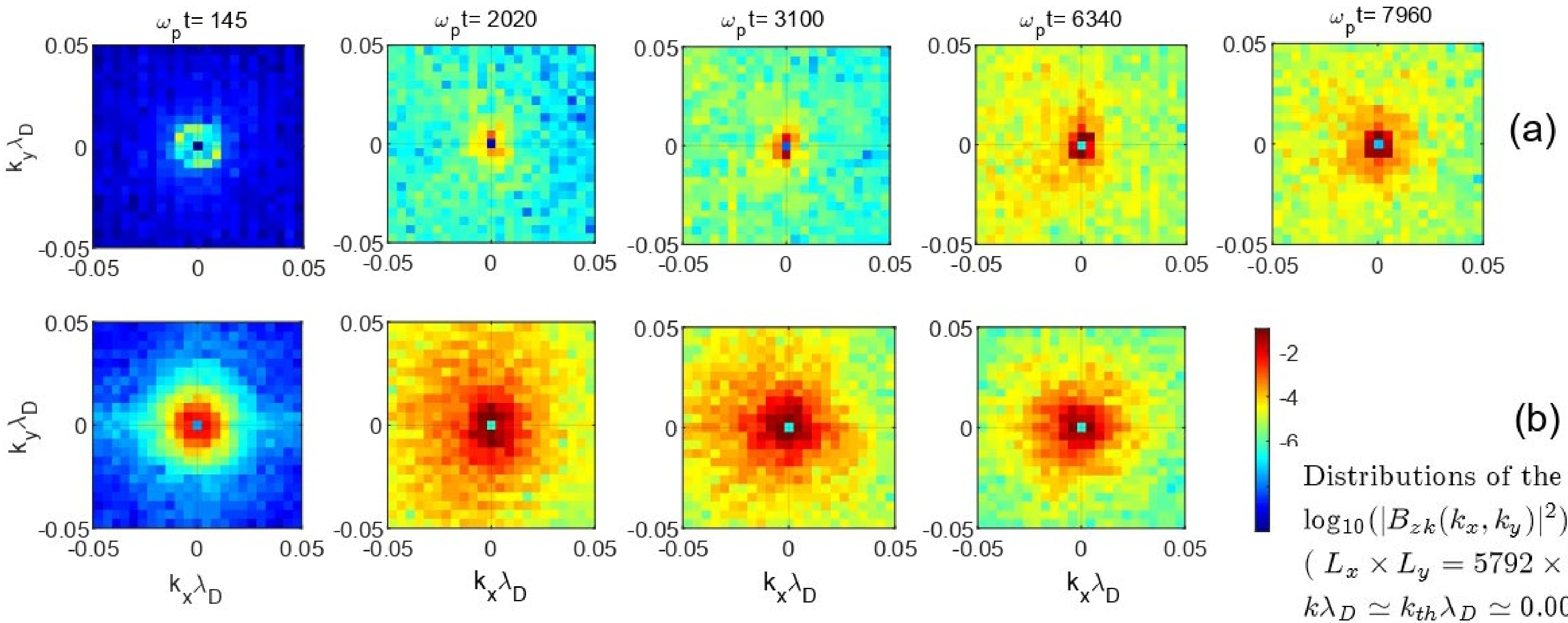
Distributions of the magnetic wave spectral energy density $\log_{10}(|B_{zk}(k_x,k_y)|^2)$ emitted at $\omega_k \simeq \omega_p$, for $\Delta N = 0.05$ ($L_x \times L_y = 5792 \times 2896\lambda_D^2$). A green circle of radius $k\lambda_D \simeq k_{th}\lambda_D \simeq 0.005$ is superposed to the spectra at the first and last times.

▶ Quasi-circular shape of radius $k\lambda_D \simeq 0.005 \sim k_{th}\lambda_D = \sqrt{3}\,(k_L\lambda_D)\,v_T/c$

$\longrightarrow$ Agreement with theory of $\mathcal{F}$ waves produced in uniform plasmas via $\mathcal{L} \pm \mathcal{S} \rightarrow \mathcal{F}$ ($\mathcal{S}$: ion acoustic waves)

Krafft and Savoini, ApJL, submitted, 2021

MAGNETIC FIELD SPECTRA $B_{zk}^2(k_x,k_y)$



Distributions of the magnetic wave spectral energy density $\log_{10}(|B_{zk}(k_x,k_y)|^2)$ emitted at $\omega_k \simeq \omega_p$, for $\Delta N = 0.05$ ($L_x \times L_y = 5792 \times 2896\lambda_D^2$). A green circle of radius $k\lambda_D \simeq k_{th}\lambda_D \simeq 0.005$ is superposed to the spectra at the first and last times.

- ▶ Strong impact of density fluctuations on the intensity and the spectral distribution of the electromagnetic emissions $\mathcal{F}$ at ω_p;
- ▶ Quasi-circular shape of radius $k\lambda_D \simeq 0.005 \simeq k_{th}\lambda_D = \sqrt{3}\,(k_L\lambda_D)\,v_T/c$;
- ▶ $\Delta N = 0$: agreement with theoretical dipolar radiation structure expected for the wave interaction processes $\mathcal{L} \pm \mathcal{S} \rightarrow \mathcal{F}$:
- ▶ $\Delta N = 0.05$: wave scattering phenomena leading to isotropization.

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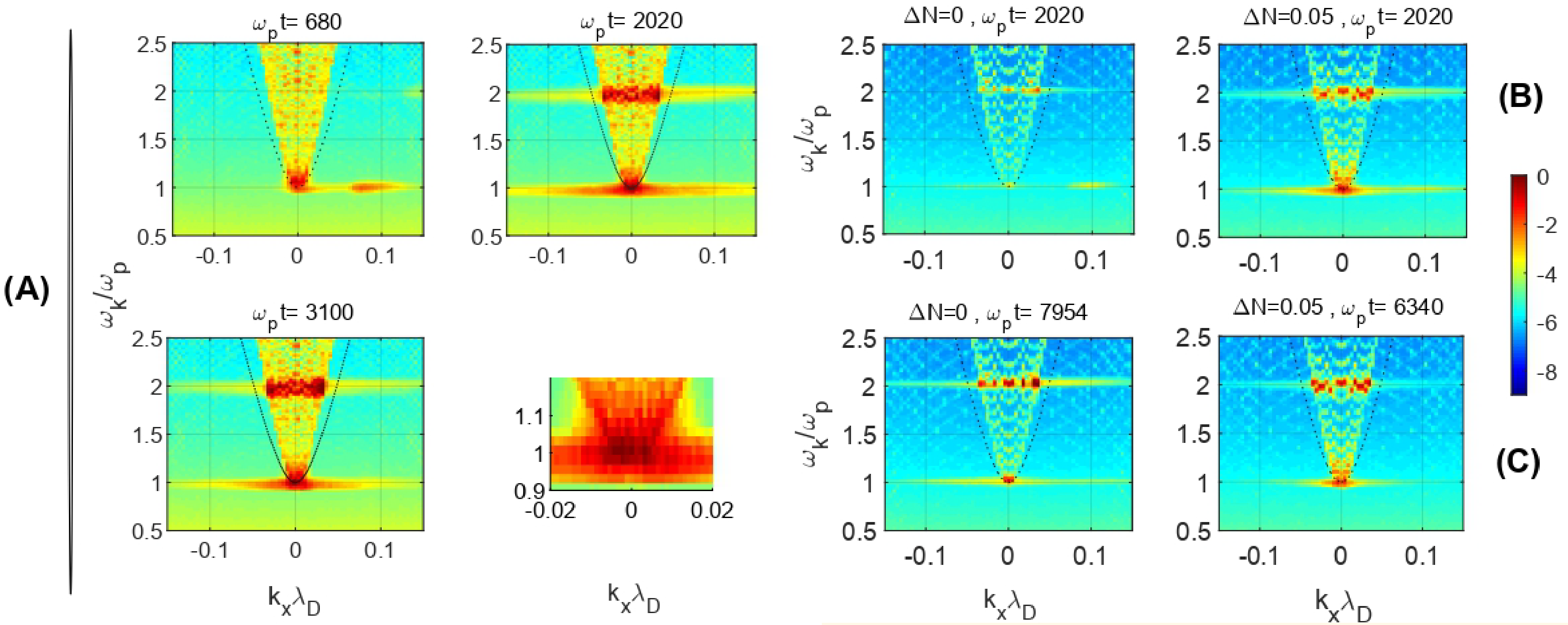
DISPERSION CURVES $B_{zk}^2(\omega_k, k_x)$



Dispersion plots of the magnetic wave spectral energy densities $\log_{10}(|B_{zk}(\omega_k, k_x)|^2)$ as a function of ω_k/ω_p and $k_x\lambda_D$, for $\Delta N = 0$ and $\Delta N = 0.05$. Panel A: dispersion plots for $\Delta N = 0.05$, at $\omega_p t = 680$, 2020 and 3100, computed with the "large" simulation box. Panel B : dispersion plots obtained using the "smaller" box, at $\omega_p t = 2020$, for $\Delta N = 0$ (left) and $\Delta N = 0.05$ (right). Panel C : dispersion plots at asymptotic times for $\Delta N = 0$ (left) and $\Delta N = 0.05$ (right); the "smaller" simulation box is used.

- Emissions of largest intensity satisfy $1 \lesssim \omega_k/\omega_p \lesssim 1.1$ and lie on dispersion curves of oblique propagating EM waves
- Harmonic $\mathcal{H}$ waves appear at $1.9 \lesssim \omega_k/\omega_p \lesssim 2.1$.
- $\Delta N = 0$: most intense emissions occur at $\omega_k \simeq 2\omega_p$, radiation at $\omega_k \simeq \omega_p$ is 2 orders of magnitude weaker.
- $\Delta N = 0.05$: strong intensification of $\mathcal{F}$ waves, due to density fluctuations.
- Asymptotic times : comparable intensities of $\mathcal{F}$ emissions for $\Delta N = 0$ and $\Delta N = 0.05$

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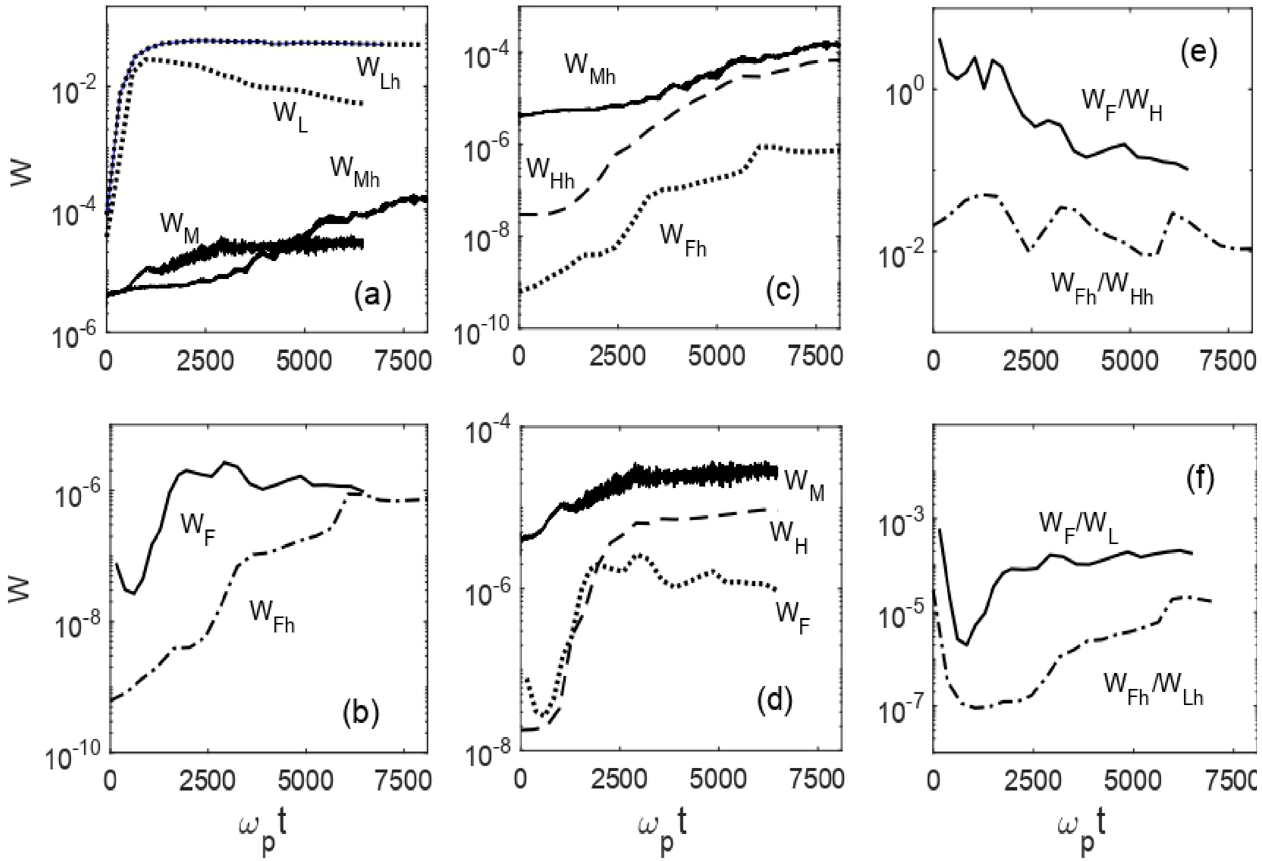
TIME VARIATIONS OF ENERGIES



Time variations of various energies W in logarithmic scales.

$W_{\mathcal{L}h}$ and $W_{\mathcal{L}}$: total Langmuir energies, for $\Delta N = 0$ and $\Delta N = 0.05$

$W_{\mathcal{M}h}$ and $W_{\mathcal{M}}$: total EM energies, for $\Delta N = 0$ and $\Delta N = 0.05$

$W_{\mathcal{F}h}$ and $W_{\mathcal{F}}$: energies of Fundamental emissions, for $\Delta N = 0$ and $\Delta N = 0.05$

$W_{\mathcal{H}h}$ and $W_{\mathcal{H}}$: energies of Harmonic emissions, for $\Delta N = 0$ and $\Delta N = 0.05$

- $\Delta N = 0$: $\mathcal{H}$ emissions dominate over $\mathcal{F}$ emissions during all evolution.
- $\Delta N = 0.05$: $\mathcal{F}$ emissions dominate $\mathcal{H}$ emissions roughly up to saturation of total EM energy.
- Strong impact of density fluctuations that enhance $\mathcal{F}$ emissions.
- At asymptotic times, $\mathcal{F}$ emissions reach the same level in plasmas with and without density fluctuations.
- Fraction of Langmuir wave energy transfered to $\mathcal{F}$ emissions $\sim 10^{-4}$ for $\Delta N = 0.05$ and $\sim 10^{-5}$ for $\Delta N = 0$.

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CONCLUSION : FUNDAMENTAL EM EMISSION

(i) Not only wave nonlinear wave interactions $\mathcal{L} \pm \mathcal{S} \rightarrow \mathcal{F}$ contribute to the generation of $\mathcal{F}$ waves, but also Langmuir waves' transformations on the density fluctuations.

(ii) $\mathcal{F}$ wave spectra show a quasi-circular shape which is significantly scattered and asymptotically isotropized by the density fluctuations, and exhibit a dipolar radiation pattern when the plasma is homogeneous.

(iii) In the homogeneous case, $\mathcal{H}$ emissions dominate over $\mathcal{F}$ emissions during all evolution. In the presence of density fluctuations, $\mathcal{F}$ wave emissions dominate $\mathcal{H}$ emissions roughly up to saturation of total EM energy.

(iv) Density fluctuations lead to a strong enhancement of $\mathcal{F}$ emissions.

(v) At asymptotic times, $\mathcal{F}$ emissions reach the same level in plasmas with and without density fluctuations.

(vi) The fraction of Langmuir wave energy transferred to $\mathcal{F}$ emissions is $\sim 10^{-4}$ (10^{-5}) when the plasma is inhomogeneous (homogeneous).