Electromagnetic radiation from wave turbulence driven by electron beams

Stellar physics (including solar physics)

Gaëtan Gauthier, Catherine Krafft, Philippe Savoini

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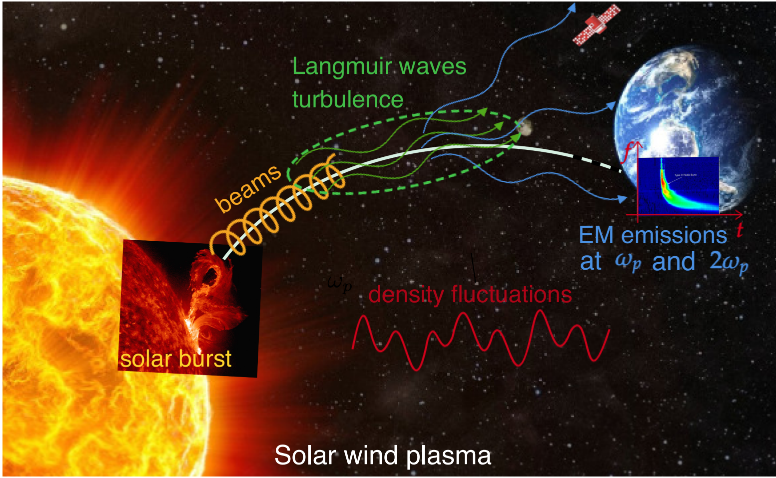
General context

Electron beams propagating in the interplanetary medium after solar eruptions or ahead of interplanetary shocks.

$\Rightarrow$ during their propagation, they are converted into **electromagnetic emissions**.

These beams can persist up to 1 UA through the **Solar Wind** (= *weakly magnetized plasma with density fluctuations*).

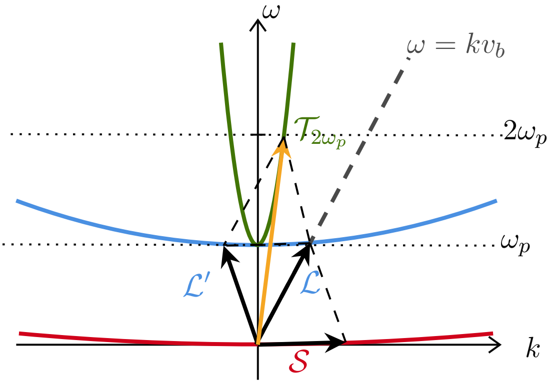


Wave coupling in homogeneous plasma

- *Electron beam* (n_b, v_b) can excite a **Langmuir wave** $\mathcal{L}$ (electrostatic) at $\omega = \omega_p$ following $\omega_p = kv_b$.
- Intense *Langmuir wave* $\mathcal{L}$ can decay into daughter waves:

$$\mathcal{L} \rightarrow \mathcal{L}' + \mathcal{S}$$

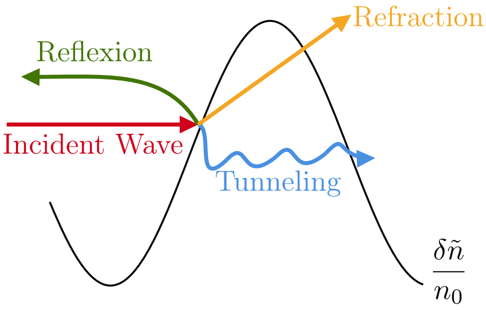
where $\mathcal{L}'$ is a backscattering *Langmuir wave* and $\mathcal{S}$ is an *ion acoustic wave* (electrostatic waves).



- Generation of an **electromagnetic wave** by *three waves interaction* at ω_p by fusion of $\mathcal{L} + \mathcal{S} \rightarrow \mathcal{T}_{\omega_p}$ and at $2\omega_p$ by $\mathcal{L} + \mathcal{L}' \rightarrow \mathcal{T}_{2\omega_p}$.

Case of inhomogenous and magnetized plasma

Modification of the analytical equations describing the waves.



- *Density fluctuations δn* modify **Langmuir wave dispersion** relationship:

$$\omega^2(k) = \omega_p^2\left(1 + 3k^2\lambda_D^2 + \frac{\delta n}{n_0}\right)$$

Thus, for density fluctuations to be large enough to cause beam Langmuir wave deresonance we require $\delta n/n_0 \geq 3k^2\lambda_D^2$.

- Adding *ambiant magnetic fields* $(\mathbf{B} \neq 0)$:

$$\omega^2(k) = \omega_p^2\left(1 + 3k^2\lambda_D^2 + \frac{\delta n}{n_0} + \frac{\omega_c k_\perp^2}{\omega_p k^2}\right)$$

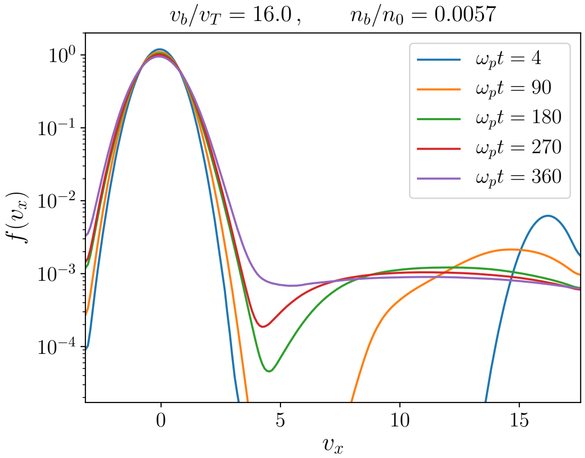
Create electron beams

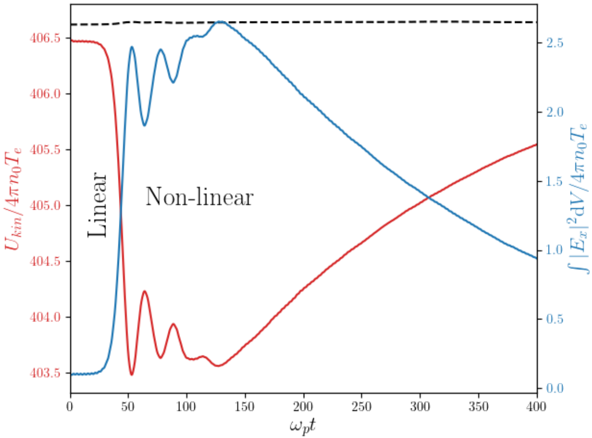
Using Smilei PIC code with *Solar Wind Physical Parameters*:

$$T_e = 200 \text{ eV}\,, \qquad T_i = T_e/10$$
$$v_b = [10; 16]\, v_T$$
$$n_b = [2 \cdot 10^{-2}; 5 \cdot 10^{-4}]\, n_0$$

Maxwellian velocity distribution for background plasma at v_T and the beams at v_b.

- After a long time, instability energy transfer **relaxes the beam** by creating a *high energy tail*.





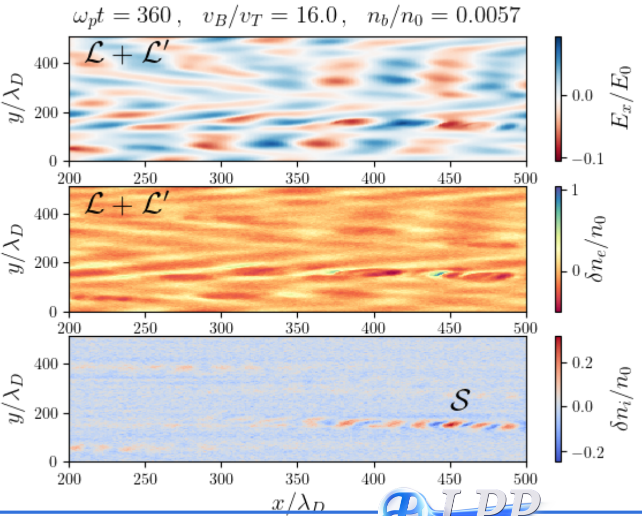
- Observation of an *exchange between kinetic and electric field energy*.
  $\Rightarrow$ instability **generates electrostatic waves** $\mathcal{L}$.
- *Linear phase* – strong transfer to fields.
- *Non-linear phase* – saturation and heating of the ambiant plasma.
- In the end stage, the kinetic energy has been transmitted into thermal energies.

Waves generation – Electrostatic stage

Generation of the backward Langmuir wave $\mathcal{L}'$.

- At the beginning ($t < 50\ \omega_p^{-1}$), instability generates *primary Langmuir waves* $\mathcal{L}$.
- At later stage ($100 < t < 200\ \omega_p^{-1}$), *secondary Langmuir waves* $\mathcal{L}'$ propagating backward develop.
- At the same time, *Ion acoustic waves* $\mathcal{S}$ appear at $k_\mathcal{S} \sim 2k_\mathcal{L}$ by **electrostatic decay**:

$$\mathcal{L} \rightarrow \mathcal{L}' + \mathcal{S}$$

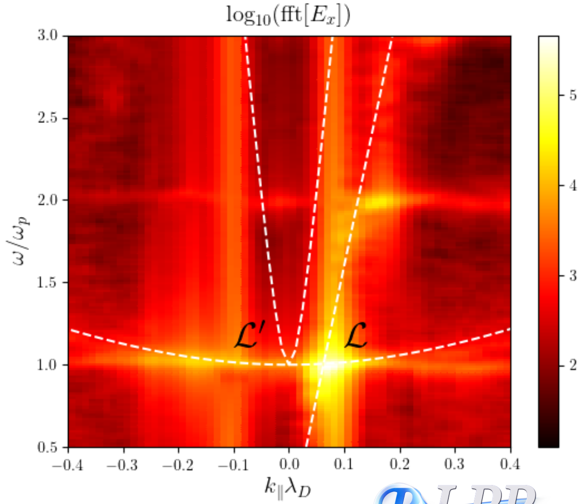


Evolution of the $\mathcal{L}$ and $\mathcal{L}'$ waves (Simulation results).

- FFT(E_x) confirms the excitation of the electrostatic *Langmuir waves* $\mathcal{L}$ at $k_{\mathcal{L}} \sim \omega_p / v_b$ by the beam.
- Presence of *second Langmuir waves* $\mathcal{L}'$ at $k_{\mathcal{L}'} < k_{\mathcal{L}}$ due to electrostatic decay satisfying **resonance conditions**:

$$\begin{cases} \omega_{\mathcal{L}}(k_{\mathcal{L}}) = \omega_{\mathcal{L}'}(k_{\mathcal{L}'}) + \omega_{\mathcal{S}}(k_{\mathcal{S}}) \\ k_{\mathcal{L}} = k_{\mathcal{L}'} + k_{\mathcal{S}} \end{cases}$$

- Note also the presence of the *second harmonic* $2\omega_p$.



Wave Generation – Electromagnetic emission

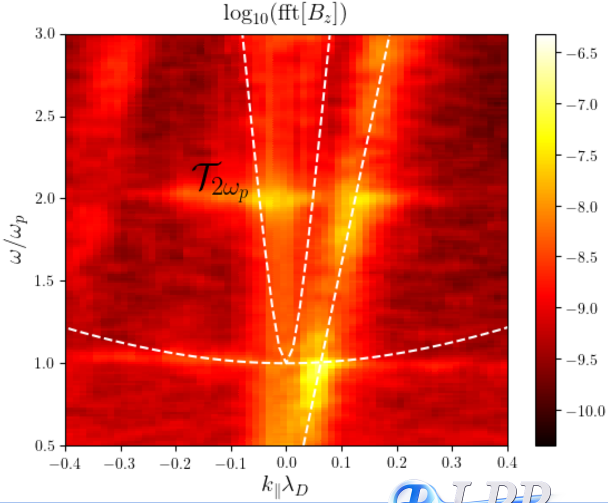
Generation of the electromagnetic waves $\mathcal{T}_{2\omega_p}$.
EM waves are identified form B_z.

- FFT(B_z) confirms the presence of a *strong emission at $\omega = 2\omega_p$* according to the EM dispersion relation.

This emission was obtained by the process of *two-plasmon fusion* :

$$\mathcal{L} + \mathcal{L}' \rightarrow \mathcal{T}_{2\omega_p}$$

⇒ Explains where the **electromagnetic emissions observed in the Solar Wind** come form (with a source of electrostatic modulations)



Zakharov idea: there exist different types of electron motions in plasmas [Zakharov 1972]:

- *Fast motion* (High frequency)
- *Slow motion* (Low frequency)

We assume that the slow motion is quasi-neutral ($\delta\tilde{n}_{\mathfrak{e}} \simeq \delta\tilde{n}_{\mathfrak{i}} \equiv \delta\tilde{n}$),

$$\begin{cases} n_{\mathfrak{i}} = n_0 + \delta\tilde{n} \\ n_{\mathfrak{e}} = n_0 + \delta\tilde{n} + \delta n_{\mathfrak{e}} \end{cases}$$

To figure out *invariants* and *Hamilton equations*, we write a hamiltonian taking into account of *density fluctuation* and an *small ambiant magnetic field* $\mathbf{B} = B_0\hat{\mathbf{z}}$ (where $\omega_c \ll \omega_p$) as:

$$\mathcal{H} = \int \left(1 + \frac{\omega_c^2}{2\omega_p^2} + \frac{\delta\tilde{n}}{2n_0}\right) \frac{\varepsilon_0}{2} \left|\nabla\varphi\right|^2 + 3\varepsilon_0\lambda_D^2 \left|\Delta\varphi\right|^2 + \frac{m_{\mathfrak{i}} n_0}{2} \left(u^2 + c_s^2 \frac{\delta\tilde{n}}{n_0}\right) \mathrm{d}V$$

Hamiltonian resolution

Our code solves these non-linear equations (in 2D) :

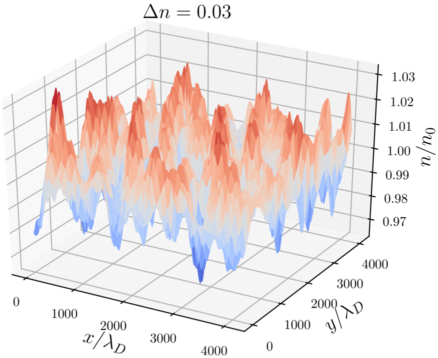
$$\nabla^2 \left(i\frac{\partial}{\partial t} + \frac{3}{2}\lambda_D^2 \omega_p \nabla^2 \right) \varphi - \frac{\omega_c}{2\omega_p}\nabla_\perp^2 \varphi = \frac{\omega_p}{2}\nabla \cdot \left(\frac{\delta\tilde{n}}{n_0}\nabla\varphi \right)$$

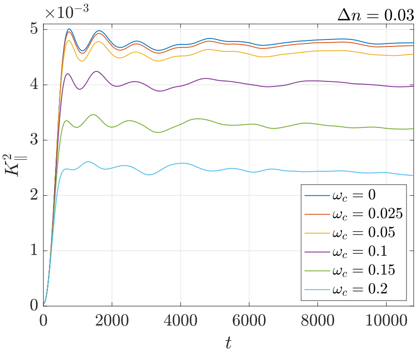
$$\left(\frac{\partial^2}{\partial t^2} - c_s^2 \nabla^2 \right) \frac{\delta\tilde{n}}{n_0} = \nabla^2 \varepsilon_0 \frac{|\nabla^2 \varphi|}{2 n_0 m_i} = 0$$

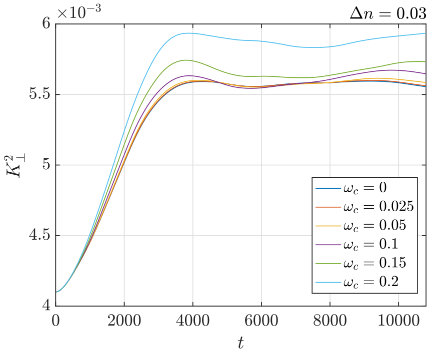
$$\frac{\partial}{\partial t}\frac{\delta\tilde{n}}{n_0} = -\nabla \cdot \mathbf{u}$$

Resolution with **realistic conditions** of the Solar Wind :

- *density inhomogeneities* $\Delta n = \sqrt{\langle (\delta n/n_0)^2 \rangle}$ where $0 \leq \Delta n \leq 0.07$,
- *weakly magnetized plasma* $\omega_c \ll \omega_p$.







Wave energy spectrum's diffusion process along $\parallel$ and across $\perp$ the magnetic field,

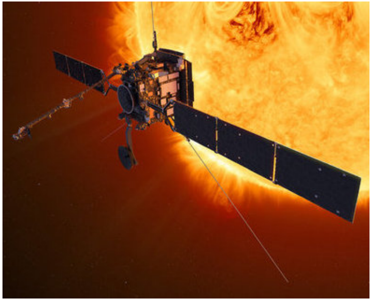
$$K_{\perp} = \frac{\int k_{\perp} |E_k|^2 \mathrm{d}V}{\int |E_k|^2 \mathrm{d}V} \qquad K_{\parallel} = \frac{\int k_{\parallel} |E_k|^2 \mathrm{d}V}{\int |E_k|^2 \mathrm{d}V}$$

$\Rightarrow$ **Magnetic term's impact** : intensification of plasma anisotropy

Conclusions

Conclusion :

- *PIC simulations* maked possible to follow in time **the generation of different waves**: $\mathcal{L}$, $\mathcal{L}'$, $\mathcal{S}$ and $\mathcal{T}$ (electrostatic and electromagnetic).
- **EM emission processes of $2\omega_p$** are important to understand the kinetic energy transferred from electron beams to radio waves.
- Very precise measurements of *Parker Solar Porbe*, *Solar Orbiter* and *Bepi Colombo* missions could be interpreted by this type of studies.



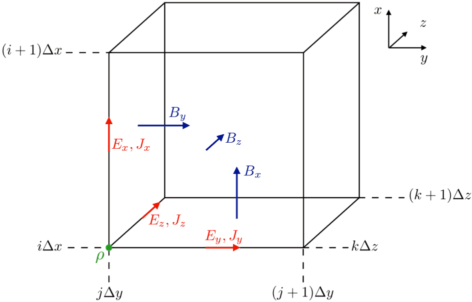
Forthcomming :

- Observation of the fundamental EM emission at ω_p (larger simulation box).
- Complete magnetic studies with PIC simulations.

What is a PIC code ?

SMILEI is a Particle-In-Cell (PIC) code for plasma simulation. Open-source, collaborative, user-friendly and designed for high performances on super-computers, it is applied to a wide range of physics studies [Derouillat et al, 2018].

- The *kinetic description* of a collisionless plasma relies on the so-called Vlasov-Maxwell system of equations.
- The PIC method owes its name to the discretization of the distribution function f_s as a sum of N_s *quasi-particles*.
- Maxwell's equations are solved here using the *Finite Difference Time Domain* approach (Yee grid).



More informations see: `http://www.maisondelasimulation.fr/smilei/`.