Hybrid-Vlasov simulations of solar-wind turbulence at short scales

F. Valentini,[1,2] F. Califano,[1] P. Veltri [2]

[1] Dipartimento di Fisica and CNISM, Università di Pisa, Pisa, Italy
[2] Dipartimento di Fisica and CNISM, Università della Calabria, Rende (Cs), Italy

ABSTRACT: The cooling of the expanding solar wind is less efficient than expected. Scientists pointed out that the reason of this empirical evidence is related to the turbulent character of the solar wind plasma. The identification of the physical mechanism replacing "energy dissipation" in a collisionless magnetized plasma and establishing the link between macroscopic and microscopic scales would open a new scenario of broad importance in the field of turbulence and space plasma heating. Turbulent heating consists both in a progressive energy degradation and disorder increasing, going from large to small scales. The increase of disorder results into the production, through nonlinear interactions, of small-scale fluctuations involving not only the kinetic energy, as in the case of heat, but also the potential energy associated with electric and magnetic field fluctuations. In this scenario, the understanding of the short-scale dynamics of the solar wind plasma, which is presumably driven by kinetic effects, is a point of key relevance in space plasma physics.

Hybrid Vlasov-Maxwell equations:

$$\frac{\partial f}{\partial t}+\mathbf{v}\cdot\nabla f+(\mathbf{E}+\mathbf{v}\times\mathbf{B})\frac{\partial f}{\partial \mathbf{v}}=0,$$

$$\mathbf{E}-\lambda_e^2\Delta\mathbf{E}=-(\mathbf{u}\times\mathbf{B})+\frac{1}{n}(\mathbf{j}\times\mathbf{B})+\frac{1}{n}\lambda_e^2\nabla\cdot\boldsymbol{\Pi}-\frac{1}{n}\nabla P_e$$
$$+\frac{1}{n}\lambda_e^2\nabla[\mathbf{uj}+\mathbf{ju}]-\frac{1}{n}\lambda_e^2\nabla\left(\frac{\mathbf{jj}}{n}\right),$$

$$\frac{\partial \mathbf{B}}{\partial t}=-\nabla\times\mathbf{E},\quad \nabla\times\mathbf{B}=\mathbf{j}.\quad P_e=(\beta/2)nT_e/T_i$$

$$\bar{u}=V_A;\quad \bar{\omega}=\Omega_{ci};\quad \bar{l}=V_A/\Omega_{ci}=c/\omega_{pi}=\lambda_i;\ \bar{n};$$

$$\omega_{pi}=4\pi\bar{n}e^2/m_i;\quad \omega_{pe}=4\pi\bar{n}e^2/m_e;$$

$$\bar{P}_{p/e}=\bar{n}m_iV_A^2;\quad \bar{E}=m_iV_A\Omega_{ci}/e;\quad \bar{B}=m_ic\Omega_{ci}/e$$

$$\beta=2v_{th,i}^2/V_A^2\qquad \lambda_e=\sqrt{(m_e/m_i)}.$$

F. Valentini et al., J. Comput. Phys. 225, 753 (2007)

Numerical setup of 1D-3V simulations:

$$\mathbf{B}_0 = B_0\hat{\mathbf{e}}_x;\mathbf{k} = k\hat{\mathbf{e}}_x$$

$$N_x = 2048; N_{v_x} = N_{v_y} = N_{v_z} = 51$$

$$L_x \approx 40\lambda_i;\lambda_e^2 = m_p/m_e = 1836;$$

$$\beta = 0.5$$

Numerical setup of 2D-3V simulations:

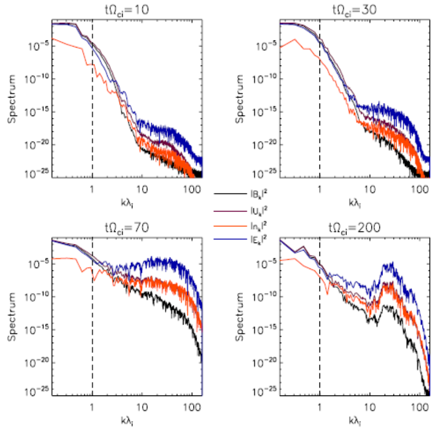
$$\mathbf{B}_0 = B_0\hat{\mathbf{e}}_x;\mathbf{k} = k_x\hat{\mathbf{e}}_x + k_y\hat{\mathbf{e}}_y$$

$$N_x = N_y = 256; N_{v_x} = N_{v_y} = N_{v_z} = 51$$

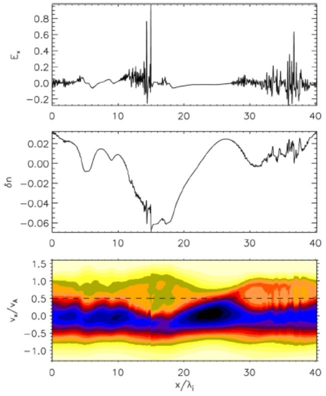
$$L_x = L_y \approx 40\lambda_i;\lambda_e^2 = m_p/m_e = 100;$$

$$\beta = 0.5$$

The electrons are isothermal. We perturb the initial equilibrium with large wavelength velocity and magnetic perturbations of the Alvenic type



Energy spectra at four different times: magnetic energy (black line), electric energy (blue line), kinetic energy (purple line), and density (red line).

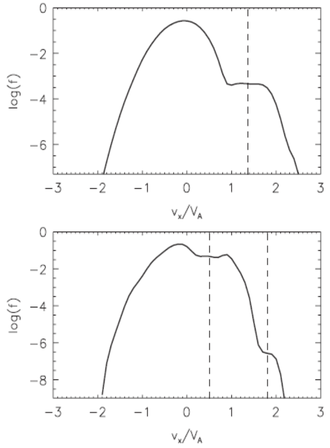


(Top plot): parallel electric field (normalized to $E_0 = m_iV_A\Omega_{ci}/e$, e being the electric charge) versus x at $t = 100$. (Middle plot): density fluctuations versus x at $t = 100$. (Bottom plot): x-v_x level lines of the reduced distribution $\hat{f}$ at $t = 100$.

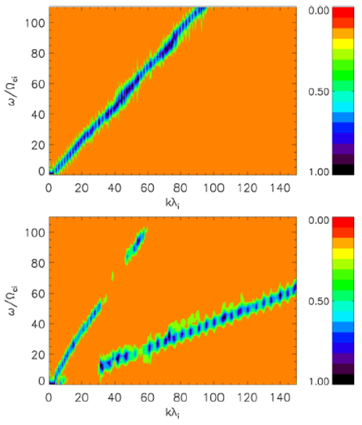
F. Valentini et al., Phys. Rev. Lett. 101, 025006 (2008)

$$D_R = 1-\frac{c_s^2}{n_0}\mathrm{P}\int\frac{(\partial f_0/\partial v_x)dv_x}{v_x-v_\phi};\quad D_I=-\cancel{\frac{\pi c_s^2}{n_0}}\frac{\partial f_0}{\partial v_x}\Big|_{v_\phi}.\quad D_R = 0\ \ (T_e/T_i = 10)\ \begin{cases}\omega_R^{IA}\approx 3.72kv_{th,i}\\ \omega_R^{IB}\approx 1.45kv_{th,i}\end{cases}$$

F. Valentini et al., Phys. Plasmas 13, 052303 (2006)

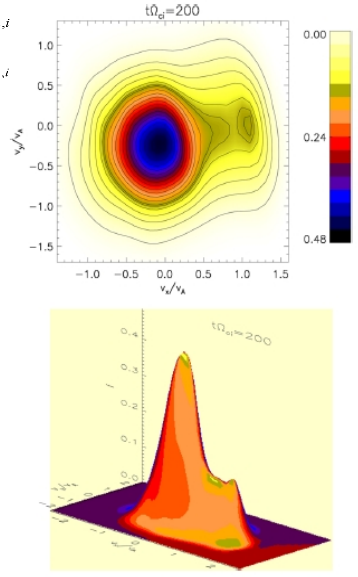


The trapping plateaus of $\hat{f} = \int f dv_y dv_z$, at $t = 200\Omega_{ci}^{-1}$, for the simulation with RH pump waves (top panel) and with LH pump waves (bottom panel).



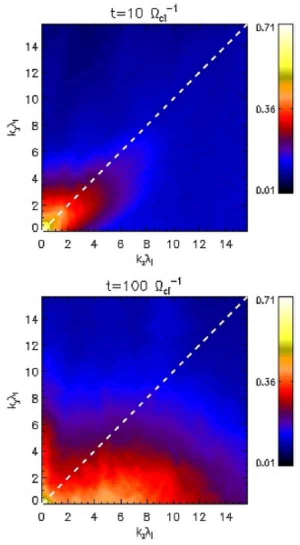
Numerical k-ω spectrum of the electric energy for the simulation with RH pump waves (top panel) and with LH pump waves (bottom panel).

F. Valentini et al., Phys. Rev. Lett. 102, 225001 (2009)

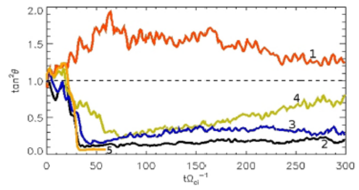


Level lines (at the top) and surface plot (at the bottom) of f in the velocity plane v_x-v_y at $t = 200$.

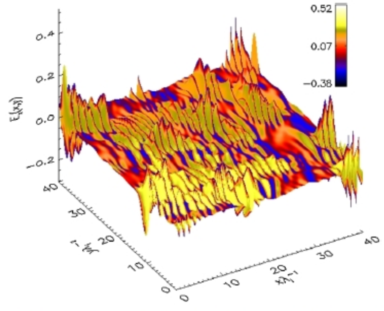
2D-3V simulations:



The 2D (k_x, k_y) spectrum of the electric energy at $t = 10$ and $t = 100$, for $T_e/T_i = 10$.



Time history of $\tan^2\theta$ for simulations with different values of T_e/T_i.



Surface plot of the parallel electric field in the (x, y) plane at $t = 50$.

F. Valentini et al., Phys. Rev. Lett. 104, 205002 (2010)