HALL-MHD SIMULATIONS OF PLASMA TURBULENCE

E. Papini[1], L. Franci[2], S. Landi[1], P. Hellinger[3], A. Verdini[1], and L. Matteini[4]

(1) Department of Physics and Astronomy, Università degli Studi di Firenze, Italy
(2) School of Physics and Astronomy, Queen Mary University of London, UK,
(3) Astronomical Institute, Prague, Czech Republic,
(4) Observatoire de Paris, LESIA, Meudon, France

ABSTRACT

In the framework of Hall magnetohydrodynamics, we investigate the properties of plasma turbulence by means of both Hall magnetohydrodynamic (HMHD) and hybrid-kinetic particle-in-cell (HPIC) numerical simulations performed with the CAMELIA code [1]. We find that HMHD simulations are able to reproduce the magnetic spectral properties of the HPIC simulations at sub-ion scales and in agreement with solar wind observations. In particular the energy spectrum of magnetic fluctuations reproduces the Kolmogorov cascade of spectral index -5/3 at MHD scales and a cascade with a spectral index of -3 at kinetic scales. The location of the break observed in the spectrum between the MHD and the kinetic scales is also recovered. Concerning the magnetic fields, HMHD simulations are in remarkable agreement with HPIC simulations, not only at the final stage, when turbulence is fully developed, but also during the evolution and the onset of the turbulent cascade. In particular, at the time when reconnection is triggered, we retrieve the appearance at kinetic scales of a power-law cascade with the same slope in both simulations. The agreements extends to the other statistical properties, such us the kurtosis of the magnetic field. At kinetic scales, the same agreement between HMHD and HPIC simulations does not hold for other quantities, namely in the energy spectrum of the velocity. We conclude that the Hall-MHD fluid description contains most of the main ingredients that characterize plasma turbulence around sub-ion scales.

NUMERICAL SETUP

Our code integrates the nonlinear fully-compressible and viscous-resistive Hall-MHD (HMHD) equations in a 2D periodic domain. We employ the same numerical setup of the Hybrid-PIC simulation of Franci et al. (2017) [2], to allow a straightforward comparison with Hall-MHD simulations.

Units and normalizations

- space: $d_i = V_A/\Omega_i$ (ion inertial length)
- time: $\tau_A = \Omega_i^{-1}$ (inverse ion gyrofrequency)
- magnetic field: B_0 (ambient field)

Setting for Hall-MHD (HMHD) simulations

- Periodic 2D domain:
  Grid: **2048^2** Resolution Δx: $d_i/8$ Box size: 256 d_i ,
- $\mathbf{B_0}$ mean field is out of plane, along the z direction.
- Initial perturbations: large-scale Alfvénic magnetic and kinetic fluctuations are set in the *xy*-plane.
- Amplitude of fluctuations at $t = 0$, B_{rms}: 0.24 B_0 .
- Initial energy-containing scale $k_\perp d_i < 0.3$.
- **Freely-decaying turbulence.**
- Plasma beta: $\beta = 2$ (corresponding to HPIC $\beta_i = \beta_e = 1$).
- Magnetic resistivity: $\eta = 10^{-3} \rightarrow S \approx 2{\cdot}10^5$ ($\eta = 5{\cdot}10^{-4}$ in HPIC)
- Magnetic Prandtl number: $\nu/\eta = 1$

MAGNETIC RECONNECTION IN DEVELOPING TURBULENCE

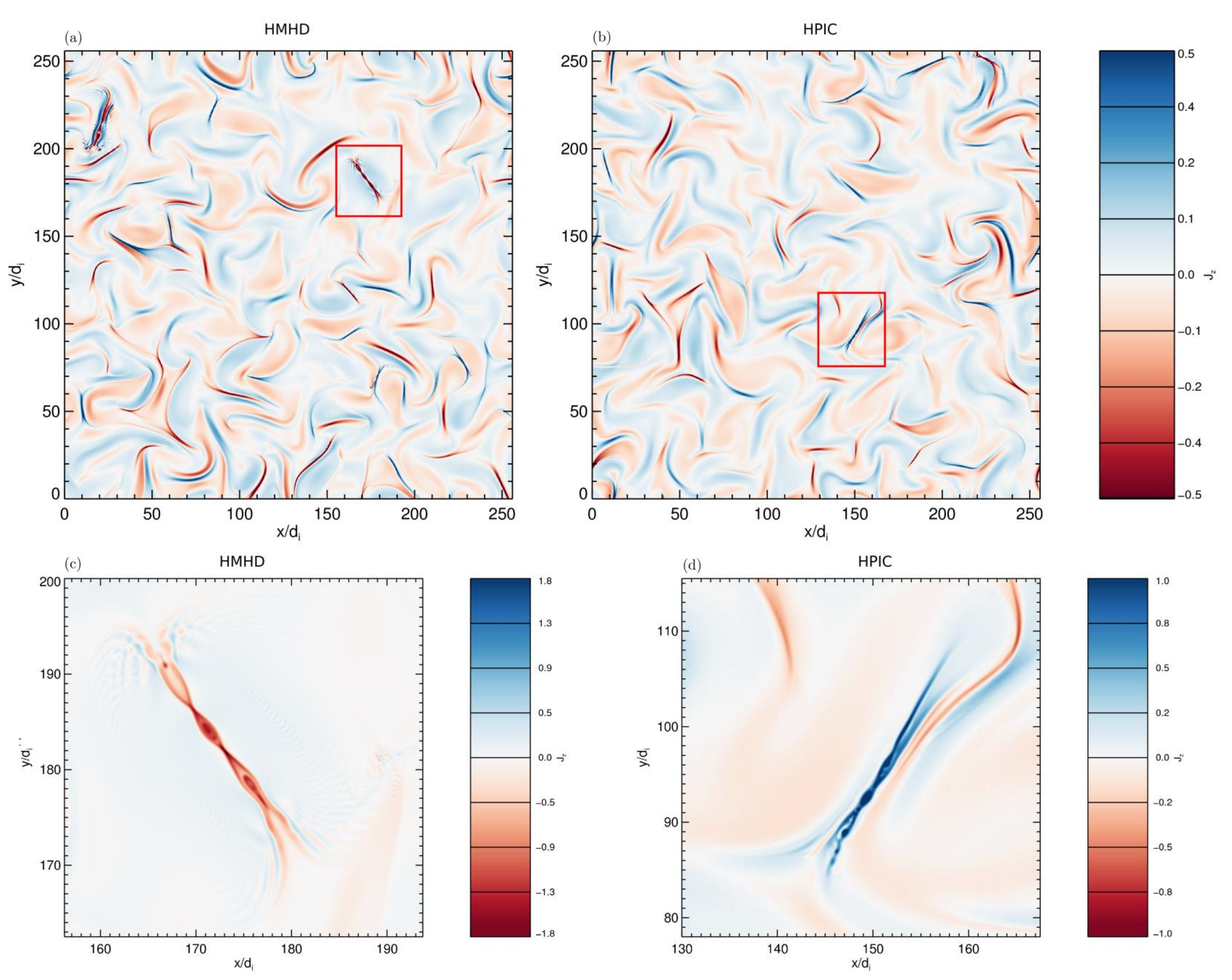


Fig. 1: Coloured contours of the out-of-plane current density, $\mathbf{J}_\parallel$, after the onset of magnetic reconnection at $t = 45\tau_A$ (HMHD) and $t = 50\tau_A$ (HPIC). Panels **(a)** and **(b)** show the full simulation box for the HMHD and the HPIC runs. Panels **(c)** and **(d)** show a zoom of two current sheets undergoing reconnection from the HMHD and the HPIC simulation respectively. Color scales are saturated to enhance contrast of coherent structures.

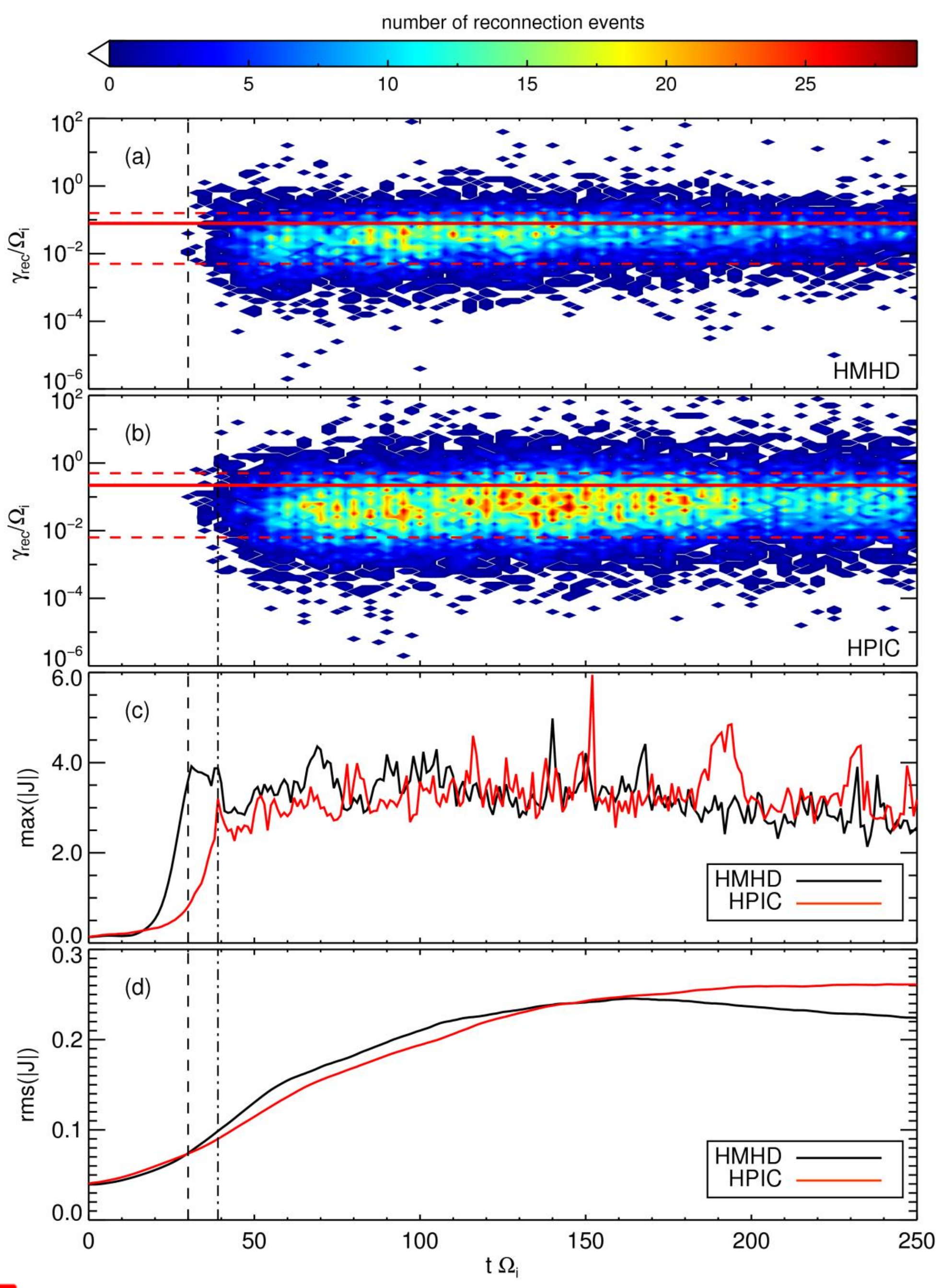
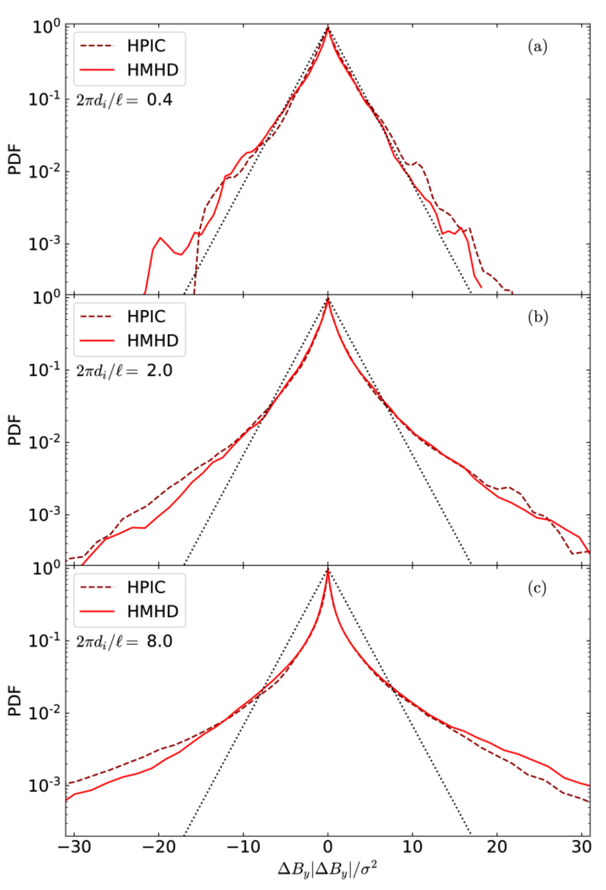


Fig. 2: Coloured contour of distribution of reconnection rates $\gamma_{\rm rec}/\Omega_i$ as a function of time for the HMHD **(a)** and the HPIC **(b)** run. Horizontal lines denote the average reconnection rate, dashed red-solid lines are the 10*th* and 90*th* percentiles. Panels **(c)** and **(d)**: time evolution of max(|**J**|) and of the rms value of |**J**|. Vertical dashed and dot-dashed lines mark the first maximum of |**J**| in the two simulations.

- ❑ In both models, reconnection occurs as soon as current sheets of thickness of few d_i form. Turbulence develops concurrently.
- ❑ Measured averaged reconnection rates of 0.08 (HMHD) and 0.22 (HPIC) agree with results from full-PIC simulations [3].
- ❑ For more than 10% of the events, the inverse reconnection rate is $< 4\tau_A$, smaller than the characteristic nonlinear time associated to the large eddies.

INTERMITTENCY



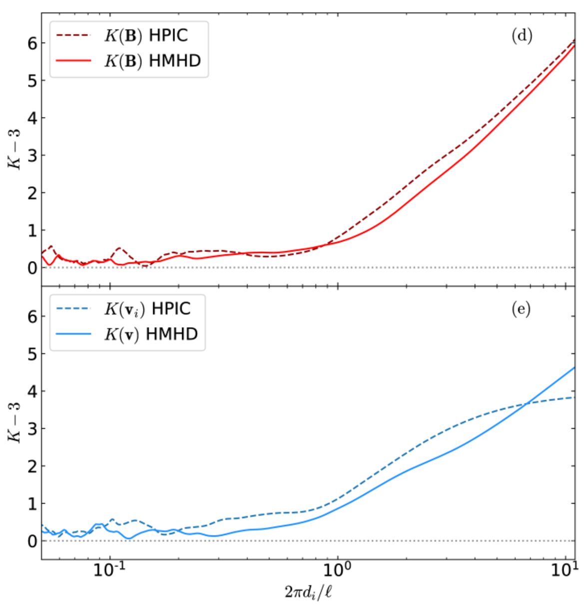


Fig. 4: Left: PDFs of the increments $\Delta B_y = B_y(x+\ell, y) - B_y(x, y)$ at three different scales ℓ: in the inertial range (a), at the spectral break (b), and at sub-ion scales (c). The dotted lines drawing a triangle correspond to a Gaussian function. The PDFs are plotted against $\Delta B_y|\Delta B_y|/\sigma^2$, with σ^2 being the variance of each PDF. Right: Scale dependent Kurtosis excess $K-3$ for the magnetic field (d) and the velocity field (e), at $t = 200\tau_A$. The horizontal dotted line denotes the zero kurtosis excess of a Gaussian function.

- ❑ Large scale PDFs of increments are consistent with a Gaussian function. Starting from scales $\ell \sim$ few d_i, corresponding to the thickness of the observed current sheets, PDFs develop non Gaussian tails.
- ❑ The magnetic field PDFs and Kurtosis of the HMHD and the HPIC models are in remarkable agreement at all scales, indicating that intermittency has the same properties in both models.
- ❑ The same agreement, but to a smaller extent, is also found in the PDFs and kurtosis of the velocity field increments.

SPECTRAL PROPERTIES OF FULL DEVELOPED TURBULENCE

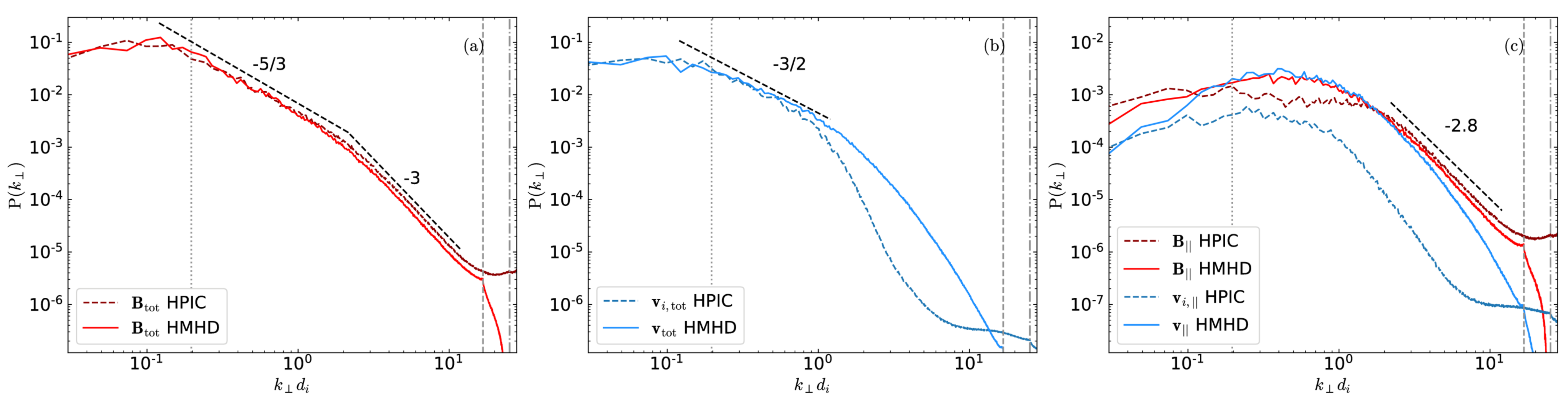


Fig. 3: 1D omnidirectional power spectra of total magnetic field fluctuations (left), total velocity fluctuations (middle), and parallel magnetic and velocity fluctuations (right). Vertical dotted, dashed, and dot-dashed lines are injection scale, 2/3 cutoff filtering (HMHD) and Nyquist frequency respectively.

- ❑ In agreement with observations [4][5], HMHD and HPIC spectra of $\mathbf{B}_{\rm tot}$ fluctuations match at all scales, and both show a power law with spectral index of -5/3 at MHD scales and **-3 at sub-ion scales.**
- ❑ The location of the spectral break at $k_\perp d_i \simeq 2$ also matches.
- ❑ Spectra of total velocity fluctuations show a power-law cascade of index -3/2 at mhd scales.
- ❑ HMHD $\boldsymbol{B}_\parallel$ and $\boldsymbol{V}_\parallel$ spectra show a strong Alfvénic coupling at MHD scales. Such coupling is not present in the HPIC spectra.

OUTLOOK

In the plasma regime studied in this work, we shown that Hall-MHD numerical simulations recover most of the properties of plasma turbulence of Hybrid-PIC simulations at sub-ion scales and routinely observed in the solar wind. In particular, the ability of HMHD to correctly reproduce the kinetic cascade of spectral index -3 in the total magnetic field spectra is most interesting. There are, however, compelling differences between the spectra of velocity fluctuations that need further investigation, in particular at the large scales where the Hybrid-PIC model and the Hall-MHD model should find the best agreement. A further study is ongoing to assess the ability of Hall-MHD to reproduce the plasma dynamics at sub-ion scales in different regimes (different plasma beta and different Reynolds numbers).

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Email contact: papini@arcetri.inaf.it