Beta Dependence of Kinetic Plasma Turbulence and Reconnection Across Scales

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Abstract

Plasma beta is an important parameter characterizing dynamics of various systems such as the solar wind, planetary magnetospheres, and accretion disks. Dependence of some plasma properties such as spectral break, relative proton-electron heating, and intermittency has been studied using observations as well as simulations [1,2,3]. In this study, we use particle-in-cell (PIC) simulations of turbulence to study various, yet unexplored, aspects of this beta variation. We analyze kinetic range electric fields, the variation of scale-to-scale energy transfer, and higher order statistics with respect to plasma beta. Systematic trends in the behavior of various quantities are discussed, and their implications for kinetic plasma dissipation are examined. Finally, we extend this approach to laminar reconnection, which shows turbulence like properties of magnetic spectrum and energy cascade [4,5]. References: Chen, et. al., Geophy. Res. Lett. 41.22 (2014); (https://doi.org/10.1002/2014GL062009) Franci, et. al., ApJ 833 91 (2016); (https://doi.org/10.3847/1538-4357/833/1/91) Parashar, et. al., ApJ Lett. 864 L21 (2018);(https://doi.org/10.3847/2041-8213/aadb8b) Adhikari, et. al., Phys. of Plasmas 27,042305 (2020); (https://doi.org/10.1063/1.5128376) Adhikari, et. al.(2021); (arXiv:2104.12013)

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Introduction:

- Study of the interplay of turbulence and reconnection has emerged as a subject of interest.

- In the past literatures, reconnection has either been studied in the presence of turbulence, or as a process subsidiary to turbulence.

- Interestingly, the kinetic simulations of reconnection is shown to exhibit a Kolmogorov (-5/3) like magnetic spectrum[1-4].

- Also, energy transfer in a standard reconnection system is found to be alike to a turbulent system [5].

- In this poster, we study the effect of plasma beta on magnetic energy spectrum, contributions to the electric field spectrum, and scale-to-scale energy transfer for kinetic turbulence.

- We also extend this approach to laminar reconnection with varying guide fields.

Theoretical Framework

- Ohm's Law:

Using the complete two-fluid model, the generalized Ohm's law can be written as:

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{1}{n}\mathbf{J} \times \mathbf{B} - \frac{1}{n}(\nabla p_e + \nabla \cdot \Pi_e) + \frac{d_e^2}{n}\left[\frac{\partial \mathbf{J}}{\partial t} + \nabla \cdot \left(\mathbf{uJ} + \mathbf{Ju} - \frac{\mathbf{JJ}}{ne}\right)\right] - \eta \mathbf{J}$$

where, u is bulk velocity, E, B are the electromagnetic fields, J is the electric current density, p_e is isotropic and Π is the anisotropic decomposition of electron pressure tensor.

- Incompressible von-Karman Howarth Equation:

The generalized von-Karman Howarth equation in an incompressible Hall-MHD system is given by:

$$\frac{1}{4}\frac{\partial S(\boldsymbol{l})}{\partial t} + \frac{1}{4}\nabla_l \cdot \mathbf{Y}(\boldsymbol{l}) + \frac{1}{8}\nabla_l \cdot \mathbf{H}(\boldsymbol{l}) = \frac{1}{2}D(\boldsymbol{l}) - \epsilon.$$

where, S is the total second order structure function, Y is the MHD flux, and H is the Hall flux. Similarly, D is the lag dependent dissipation and is ε the total dissipation rate.

Simulations:

Kinetic particle-in-cell simulations in 2.5 D setup

TABLE I. Simulation details: background density n_b, mass (m) of ions(i)/electrons(e), temperature (T), beta (β), and particles per grid (ppg).

Run	$L_x = L_y$	n_b	m_e/m_i	$T_i = T_e$	$\beta_i = \beta_e$	ppg
T1	$149.6d_i$	1.0	0.04	0.15	0.3	3200
T2	$149.6d_i$	1.0	0.04	0.3	0.6	3200
T3	$149.6d_i$	1.0	0.04	0.6	1.2	3200

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TABLE II Simulation details: background density n_b, mass (m) of ions(i)/electrons(e), temperature (T), out of plane guide field B_g, reconnecting magnetic field B_r, and particles per grid (ppg).

Run	$L_x = L_y$	n_b	m_e/m_i	T_i/T_e	B_g	B_r	β_i/β_e	ppg
R1	$204.8d_i$	0.2	0.04	0.25/1.25	0	1	0.5/0.1	100
R2	$204.8d_i$	0.2	0.04	0.25/1.25	0.1	1	$\sim 0.5/0.1$	100
R3	$204.8d_i$	0.2	0.04	0.25/1.25	0.5	1	0.45/0.09	100
R4	$204.8d_i$	0.2	0.04	0.25/1.25	1	1	0.35/0.07	100
R5	$204.8d_i$	0.2	0.04	0.25/1.25	2	1	0.22/0.044	100

RECONNECTION

Overview:

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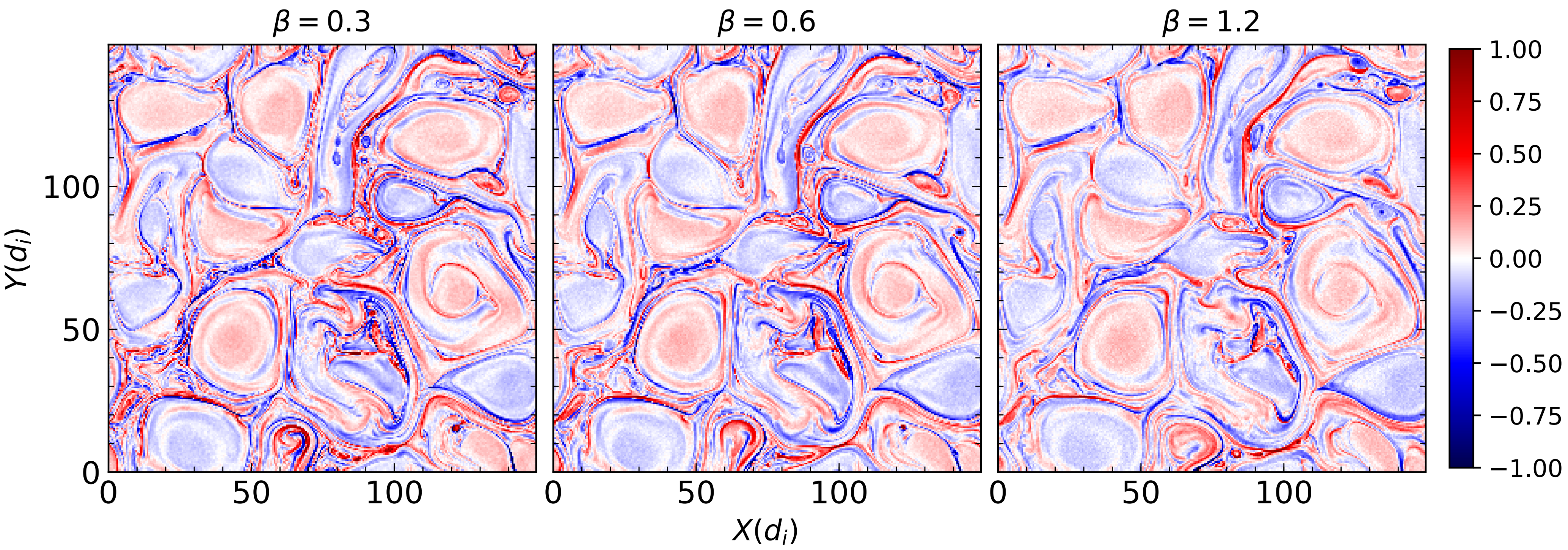

Fig. 1: Out of plane current (j_z) for turbulence simulations when the mean square current is maximum in the system.

RECONNECTION

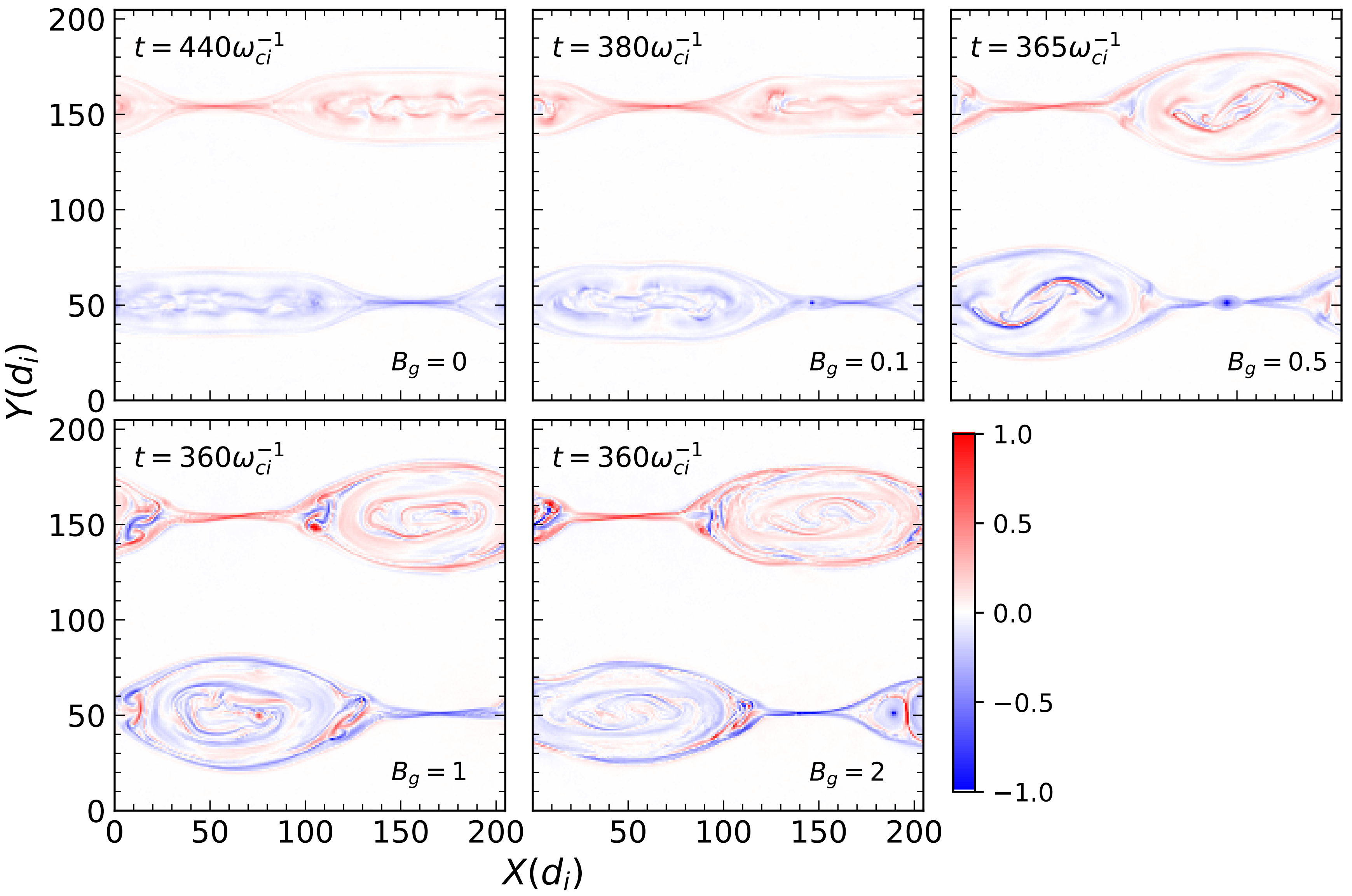

Fig. 2: Out of plane current (j_z) for reconnection simulations when the mean square current is maximum in the system.

Results:

Magnetic energy spectrum:

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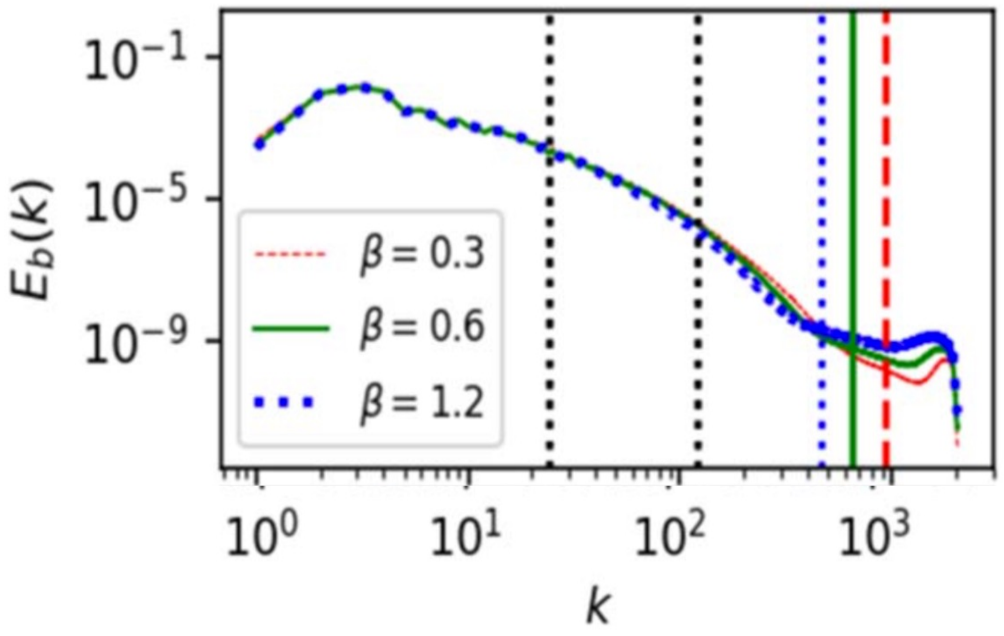

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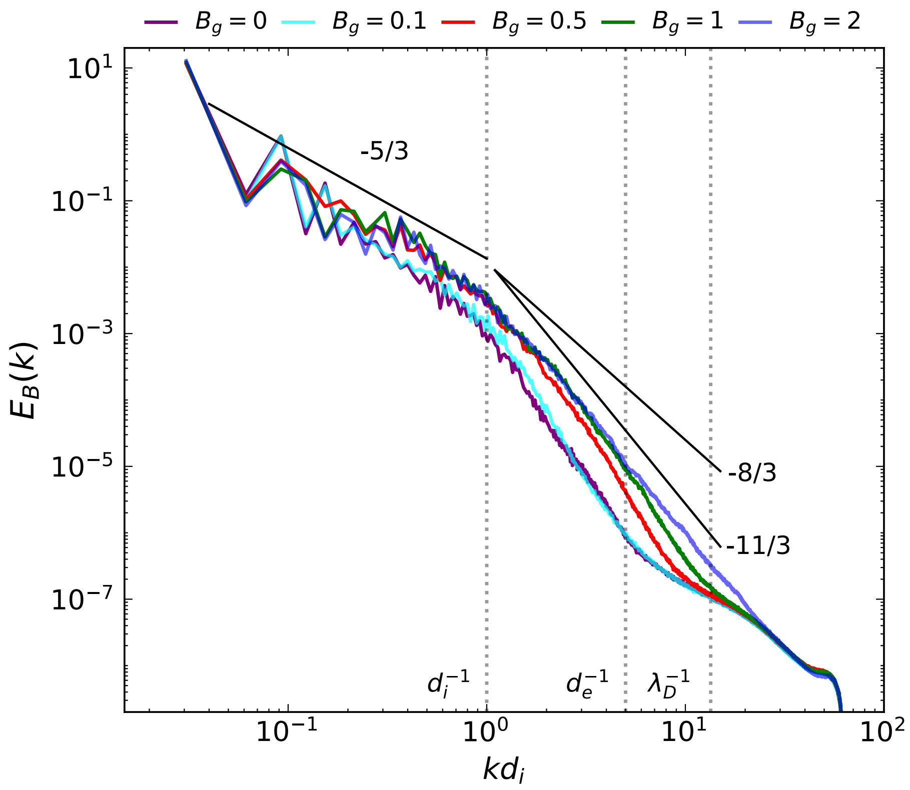

Fig. 3: Magnetic energy spectrum for various turbulence runs adopted from Parashar et al. (2018)[8] and for various reconnection runs. Solid lines of slopes -5/3, -8/3, and -11/3 are drawn for reference.

Electric field energy spectrum:

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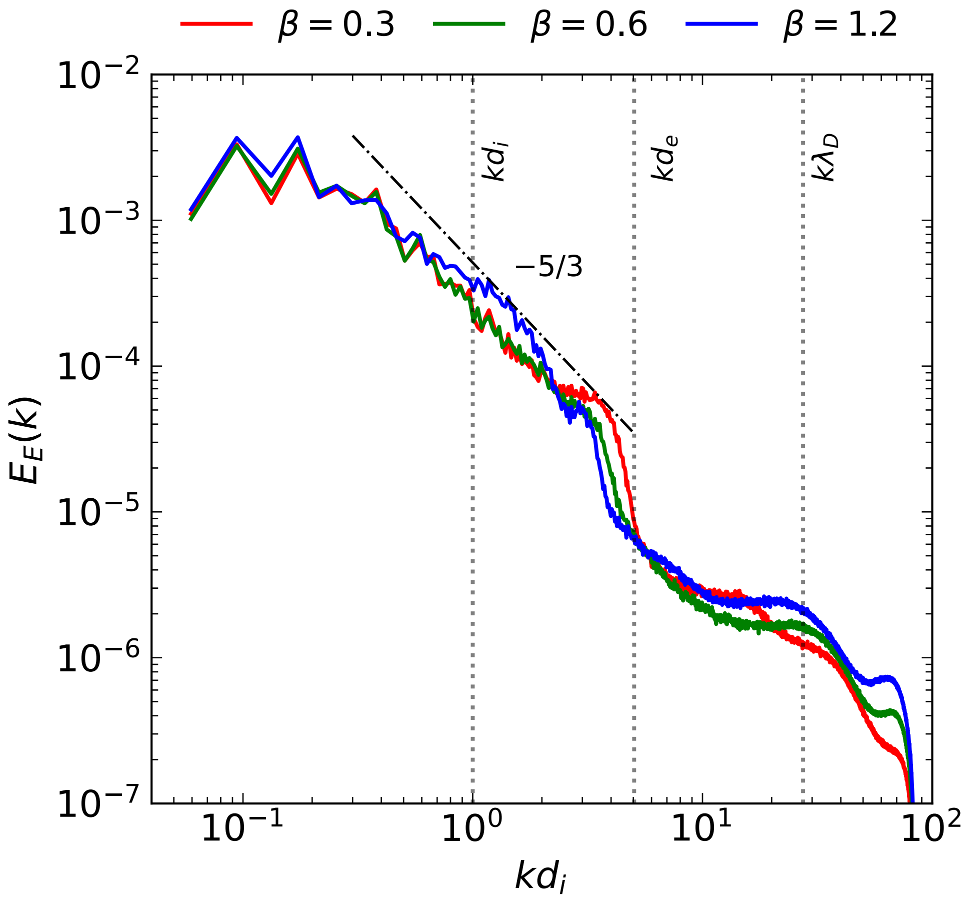

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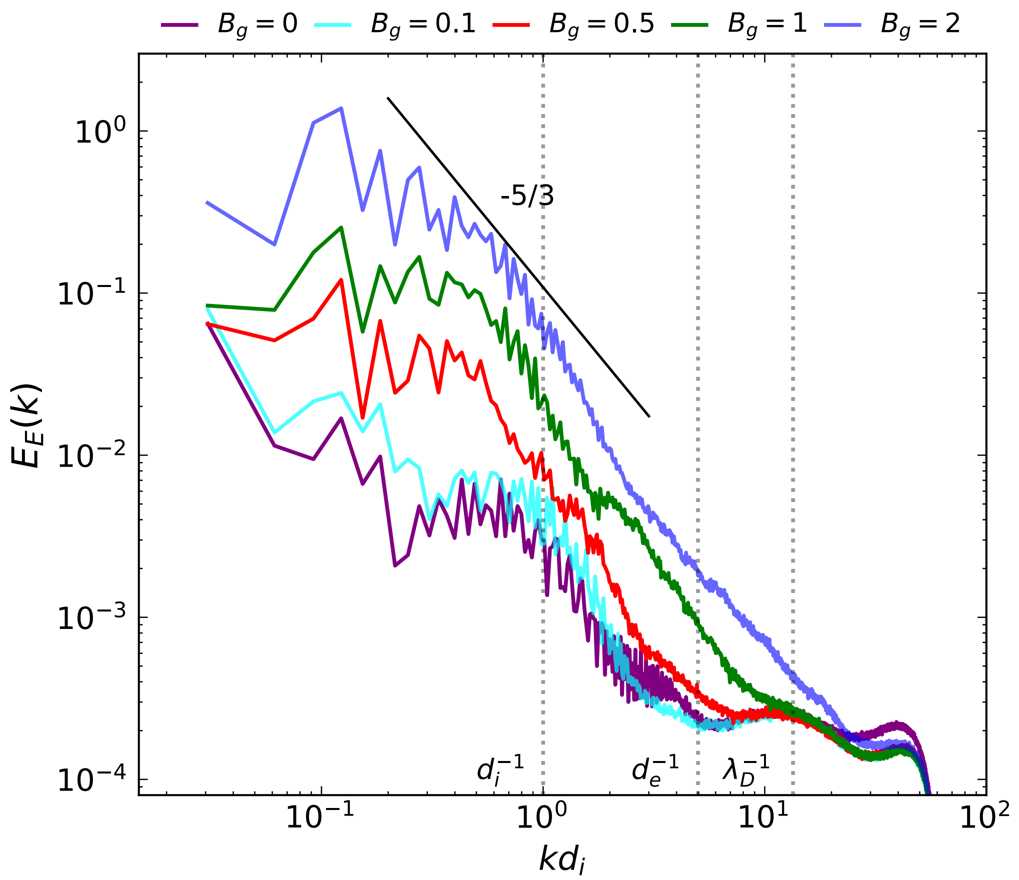

Fig 4: Energy spectrum of electric field for all the turbulence and reconnection simulations.
A solid line of slope -5/3 is drawn for reference.

Spectrum of the Ohm's law

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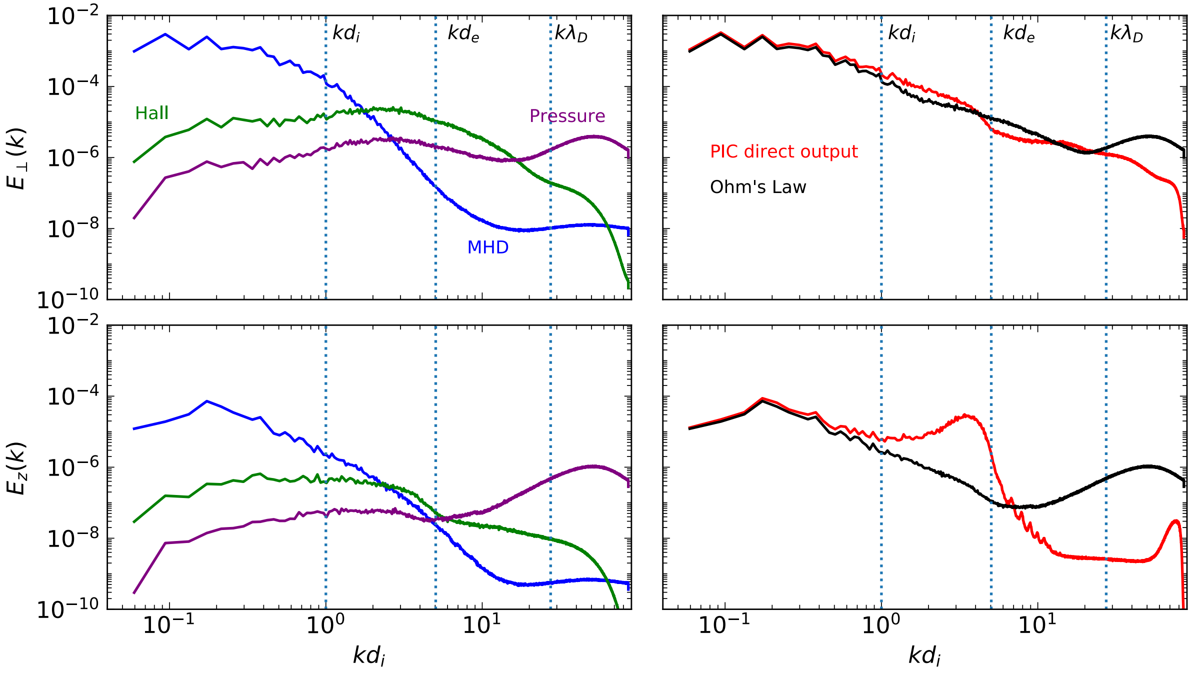

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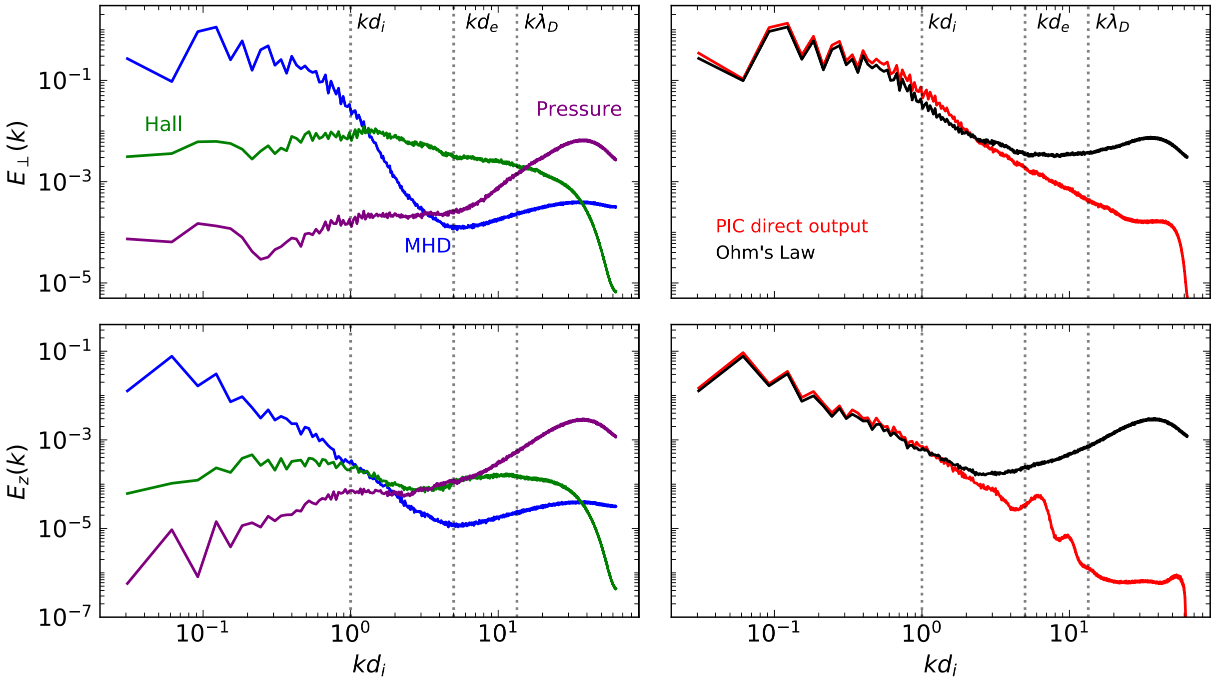

Fig. 5: Turbulence: Top panel (left): Energy spectrum of different components of perp E as seen in Ohm's law for β=0.3. (Right) Sum of all terms in the left (black), and spectrum of perp E obtained from the simulation. Bottom panel: Same as the top panel but for parallel E-field. See [7] for results from β=0.6. Reconnection: Same as turbulence but for guidefield B_g=2.

Perpendicular Electric field

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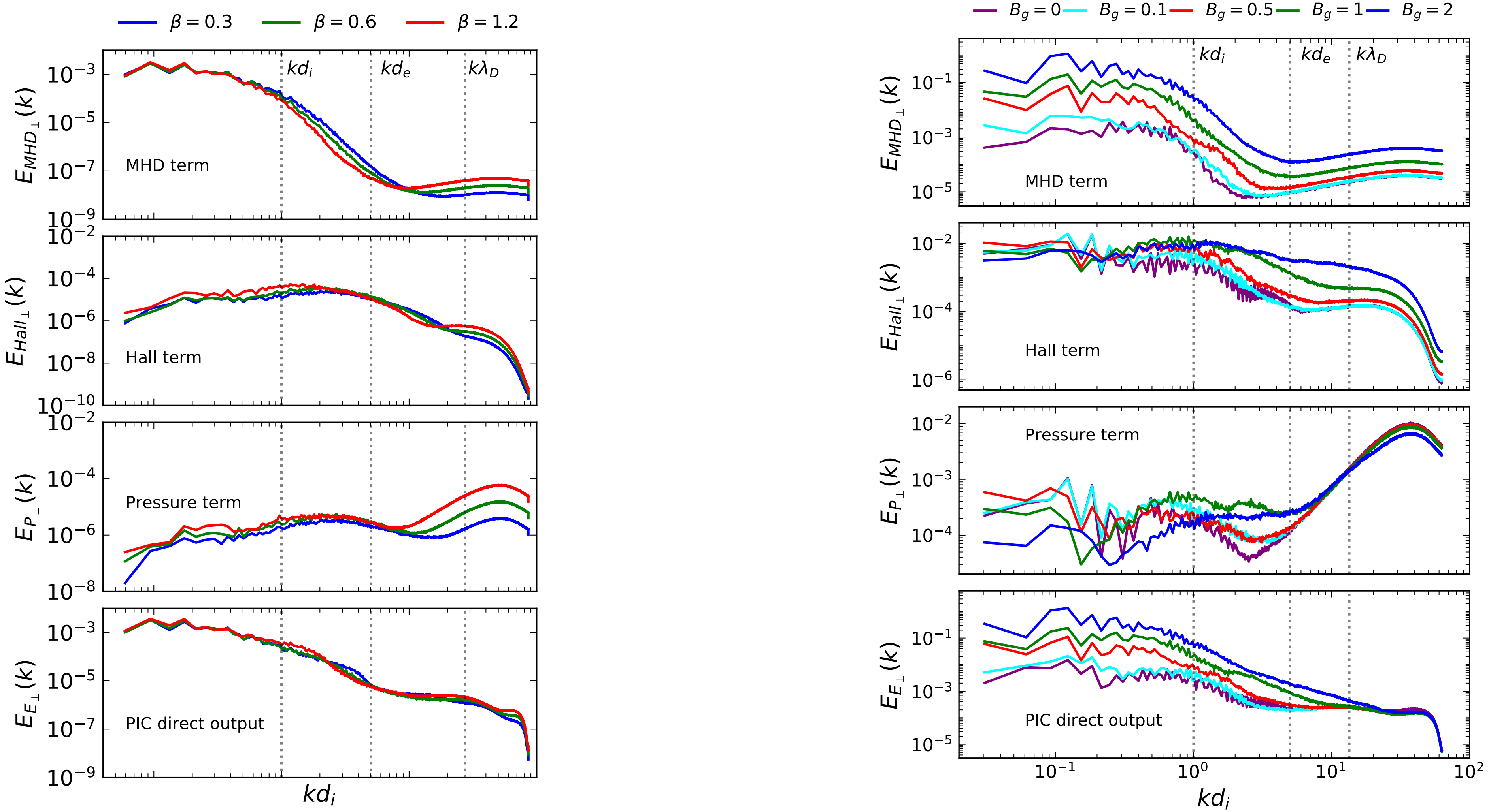

Fig 6: Perpendicular power spectra of different components of Ohm's law: MHD (top row), Hall term (second row), pressure term (third row) and the spectrum of the perpendicular electric field ($E_\perp$), obtained directly from the simulation (last row).

Parallel Electric field

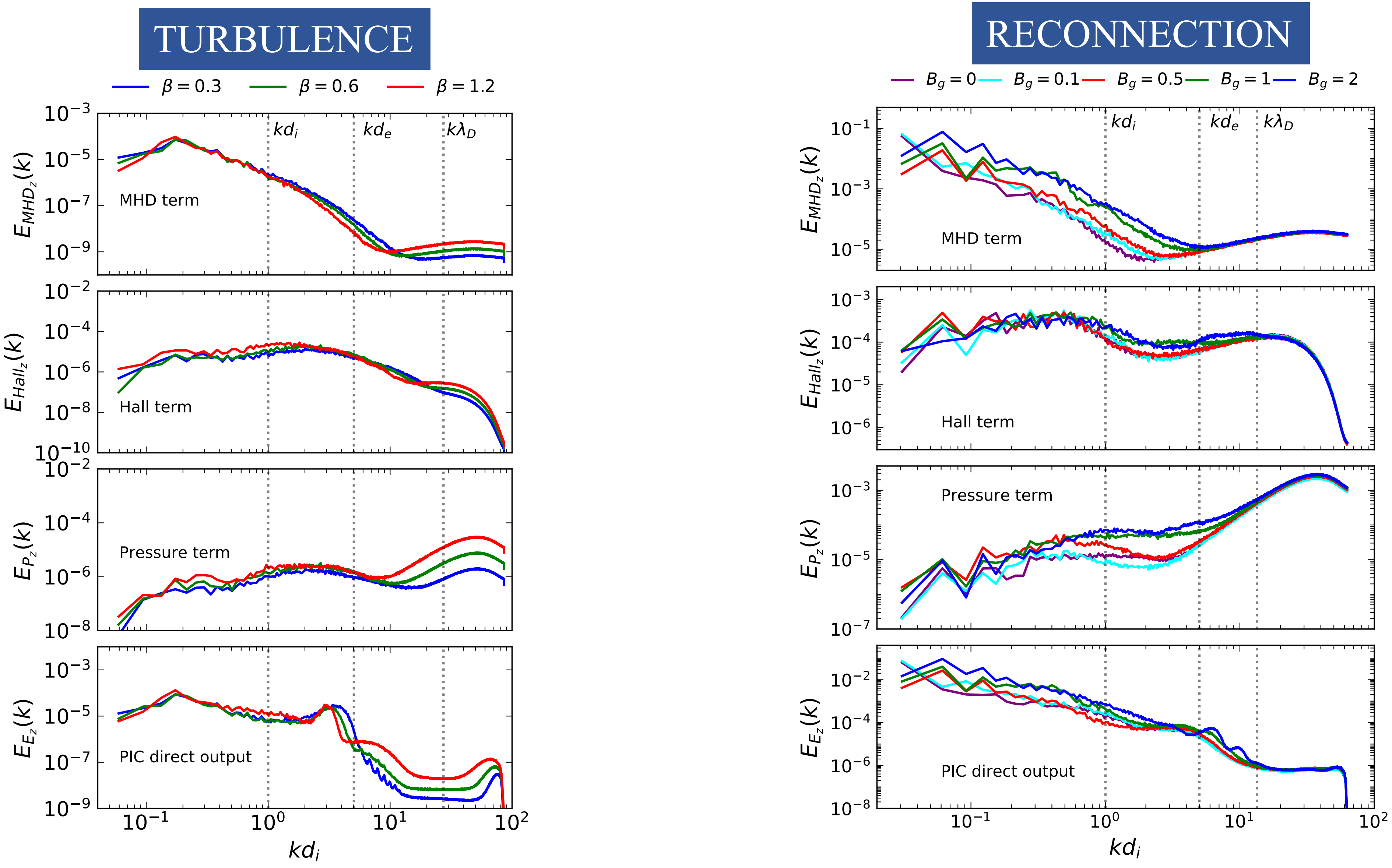

Fig 7: Parallel power spectra of different components of Ohm's law: MHD (top row), Hall term (second row), pressure term (third row) and the spectrum of the perpendicular electric field ($E_{\perp}$), obtained directly from the simulation (last row).

Incompressible von-Karman Howarth Eqn.:

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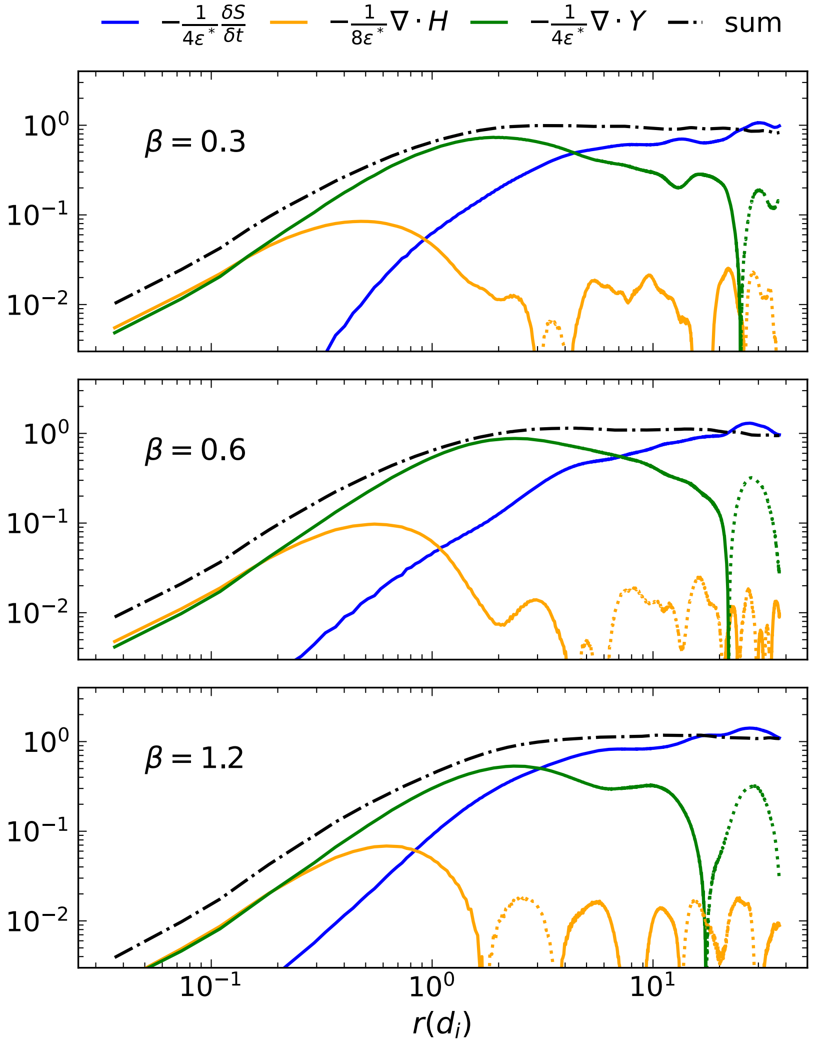

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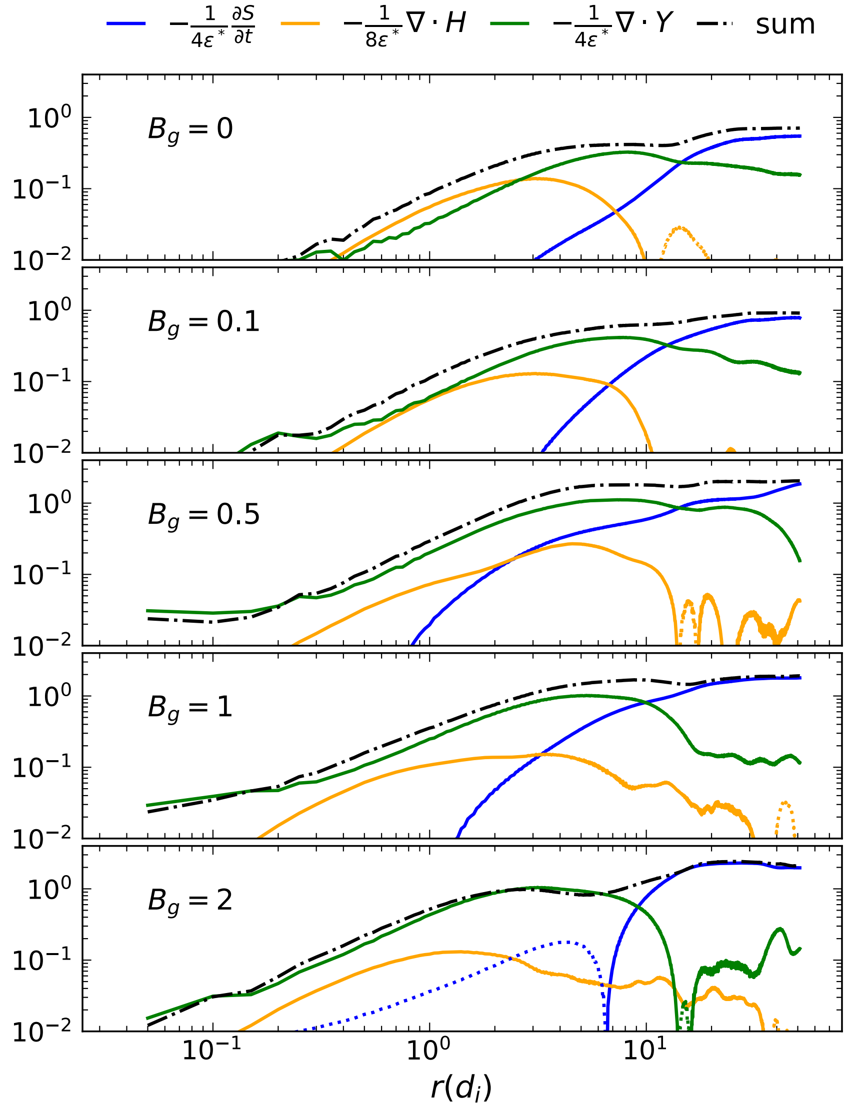

Fig 8: Individual component of the incompressible von-Karman Howarth equation for the turbulence simulations. Here, all the terms are normalized to ε*, rate of change of magnetic and ion flow energy.

Conclusions:

- The break point of magnetic field spectrum shifts towards higher wave number for low plasma beta. See [8] for results from turbulence simulations.
- For perpendicular electric field, the spectrum is dominated by the MHD component at smaller wavenumbers. The Hall term dominates the wavenumbers between the inverse of ion inertial length and the Debye length.
- For parallel electric field, the Hall term is less significant compared to the perp. case.
- Higher guide field simulations have wider Hall flux term, although the contribution to the total dissipation for smaller lags remains about the same. This is in agreement with the low beta simulations of turbulence.
- The Yaglom flux term is flat over an extended inertial length for larger guide field runs. The structure function term dominates the total dissipation significantly in the energy containing scales for higher guide field runs.
- Qualitative behavior of these quantities in turbulence and reconnection are very similar providing evidence for greater inter-relationship than previously reported.

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