Investigating the ion-scale spectral break of solar wind turbulence from low to high beta with high-resolution hybrid simulations

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ABSTRACT

We investigate the properties of the ion-scale spectra break of solar wind turbulence by means of two-dimensional high-resolution hybrid particle-in-cell simulations. We impose an initial ambient magnetic field perpendicular to the simulation box and we add a spectrum of in-plane, large-scale, magnetic and kinetic fluctuations, with energy equipartition and vanishing correlation. We perform a set of simulations with different values of the plasma beta, β, distributed over three orders of magnitude, from 0.01 to 10. In all cases, once turbulence is fully developed, the power spectrum of magnetic fluctuations follows a power law with a spectral index of -5/3 in the inertial range. In the sub-ion range we observe another power law with a spectral index varying with β (from around -3.6 for small values to around -2.9 for large ones). The two ranges are separated by a spectral break around ion scales. We identify the length scale at which such break occurs, which is found to be proportional to the ion inertial length, d_i, for $\beta \ll 1$ and to the ion gyroradius, $\rho_i = d_i \sqrt{\beta_\perp}$ for $\beta \gg 1$, i.e., to the larger between the two scales in both regimes. For intermediate cases, i.e., $\beta \sim 1$, a combination of the two scales in involved. We infer an empiric relation for the dependency of the spectral break on β that provides a good fit over the whole range of values. We compare our results with solar wind observations and suggest possible explanations for such behavior.

SIMULATIONS SETUP

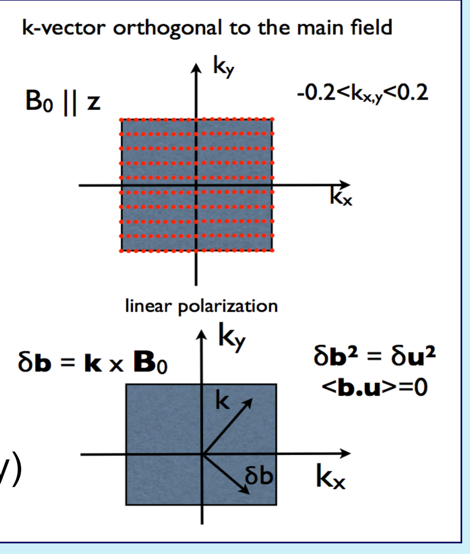
Numerical setting

Units and normalizations
- space: $d_i = v_A/\Omega_p$ (protonb inertial length)
- time: Ω_p^{-1} (inverse proton gyrofrequency)
- magnetic field: B_0 (ambient field)
- velocity: v_A (Alfvén speed)

Setting
- 2D square grids (2048^2 cell)
- $\Delta x = \Delta y \leq d_i/4$
- particles-per-cell = 1000 ÷ 16000
- resistivity ≠ 0 (fine-tuned)

Initial conditions

- $\mathbf{B}_0$ out-of-plane mean field
- In-plane magnetic and velocity fluctuations
- modes with random phases
- energy equipartition and vanishing correlation between kinetic and magnetic fluctuations
- $\mathbf{B}^{rms}/\mathbf{B}_0$ = 1/16 ÷ 1/2 (global amplitude)
- $\beta_p = \beta_e \in$ [0.01, 10] (proton and electron beta)
- $A_p = T_{p\perp}/T_{p\parallel} = 1$ (proton temperature anisotropy)

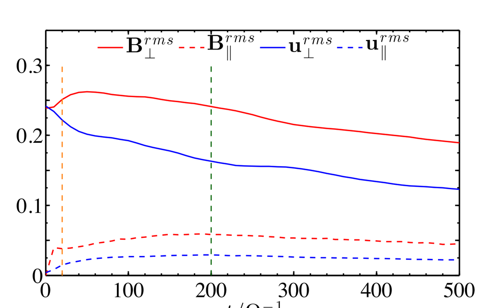


List of simulations

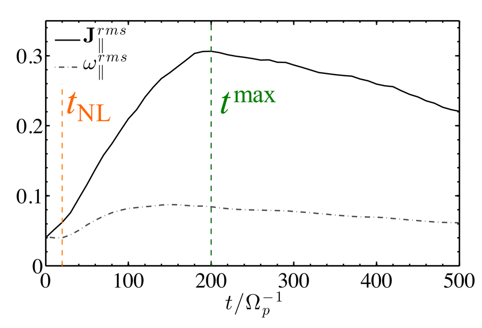
RUN	$B^{rms}(B_0)$	β	$\Delta x\ (d_i)$	ppc	α_1	α_2	$k_\perp^b d_i$
A0.06B0.01	1/16	0.01	0.125	1000	-1.60	-3.60	2.79
A0.12B0.03	1/8	1/32	0.125	1000	-1.58	-3.55	3.04
A0.24B0.06	1/4	1/16	0.125	1000	-1.53	-3.36	3.04
A0.24B0.12	1/4	1/8	0.125	2000	-1.64	-3.24	3.26
A0.24B0.25	1/4	1/4	0.125	4000	-1.63	-3.10	2.86
A0.24B0.50	1/4	1/2	0.125	8000	-1.63	-2.96	2.56 [1,2]
A0.24B1.00	1/4	1	0.125	12000	-1.59	-2.94	2.10
A0.24B2.00	1/4	2	0.125	16000	-1.60	-2.92	1.88
A0.24B4.00	1/4	4	0.125	16000	-1.71	-2.93	1.61
A0.50B6.00	1/2	6	0.25	8000	-1.69	-3.01	1.25
A0.50B8.00	1/2	8	0.25	8000	-1.70	-3.02	1.12
A0.50B10.0	1/2	10	0.25	8000	-1.72	-3.14	1.05

A CASE STUDY: β = 0.5

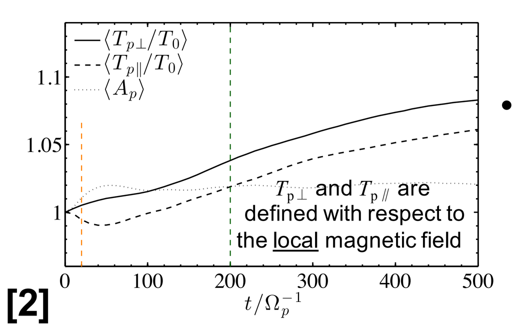
Time evolution of global and local quantities



- The large-scale activity is dominated by $\mathbf{B}_\perp$ and $\mathbf{u}_\perp$
- Magnetic islands and vortices form

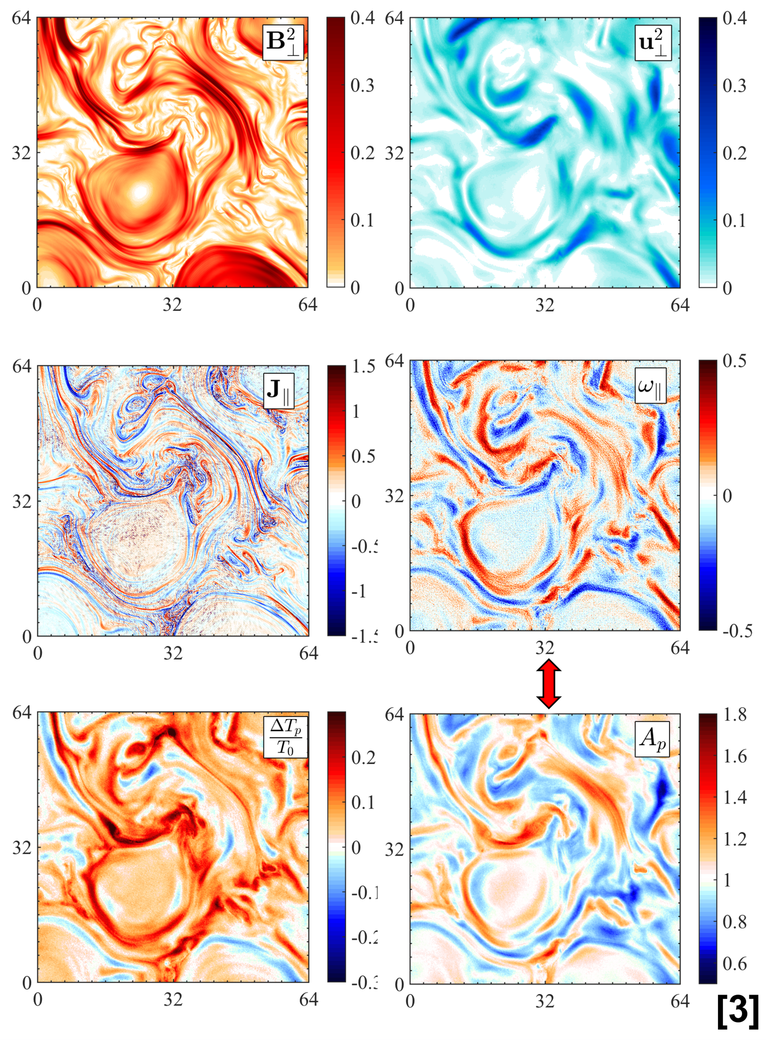


- The peak in the out-of-plane current, $\mathbf{J}_\parallel$, identifies the maximum turbulent activity
- Current sheets form and disrupt



- No preferential heating
- No global proton temperature anisotropy
- Correlation between T_p enhancements and vorticity

[2]



[3]

Spectral properties vs. solar wind observations

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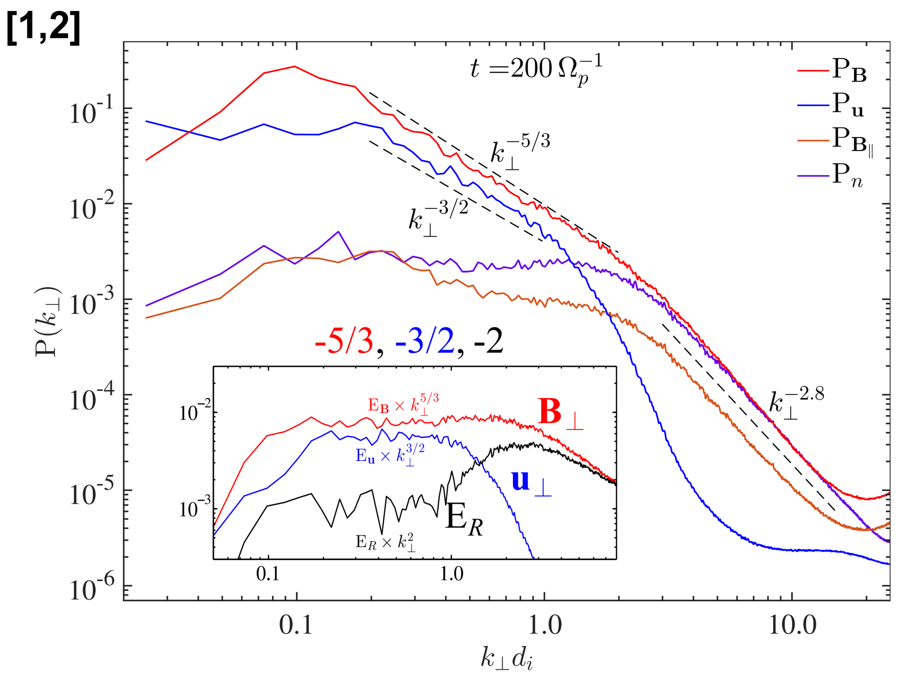
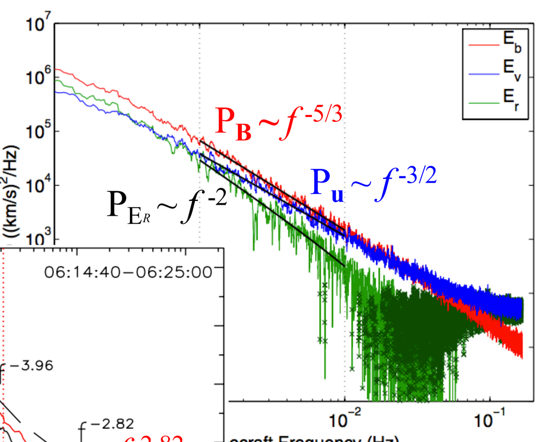


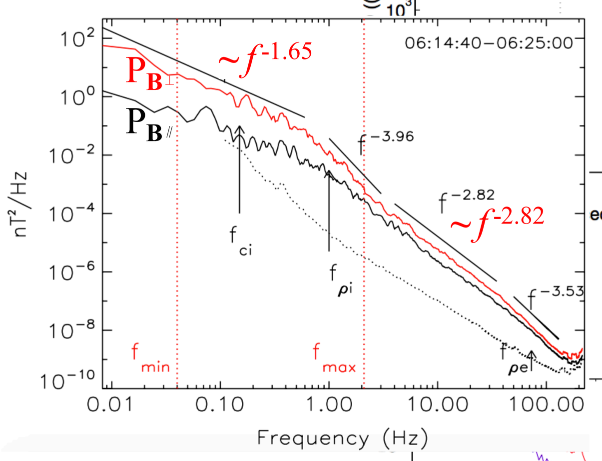
MHD inertial range
- Spectra of $\mathbf{B}_\perp$ and $\mathbf{u}_\perp$ have different power-law scaling
- Their difference (residual energy, E_R) is also a power law

Smooth break around ion scales

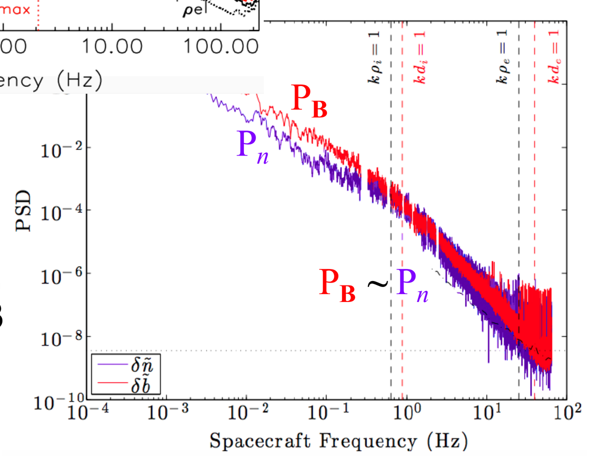
Kinetic sub-ion range
- Spectra of $\mathbf{B}_\parallel$ and n are coupled and prop. to $k_\perp^{-2.8}$
- The spectrum of $\mathbf{B}_\parallel$ gets comparable with the one of $\mathbf{B}_\perp$



Chen et al., ApJ 2013



Sahraoui et al., PRL 2010

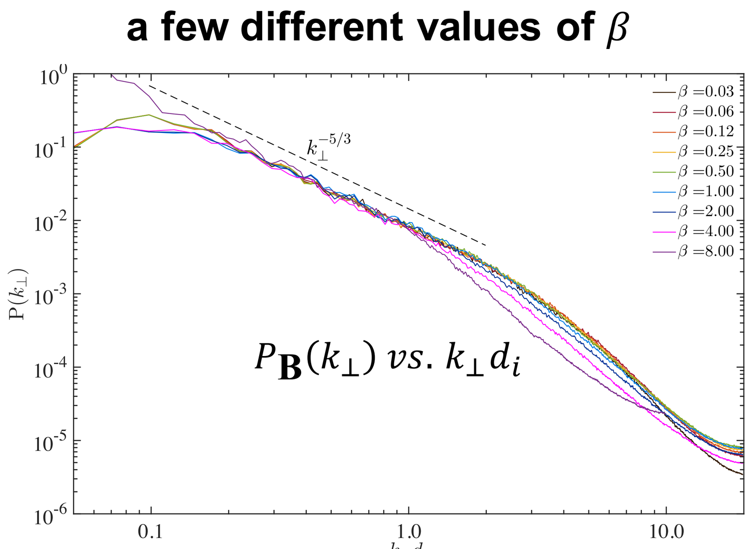


Chen et al., PRL 2013

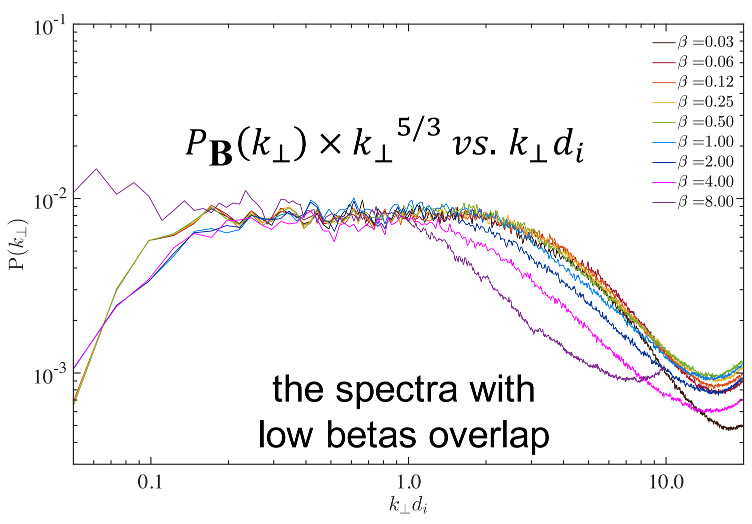
EFFECTS OF THE PLASMA BETA β

[4]

Power spectra of magnetic fluctuations for a few different values of β



Compensated spectra



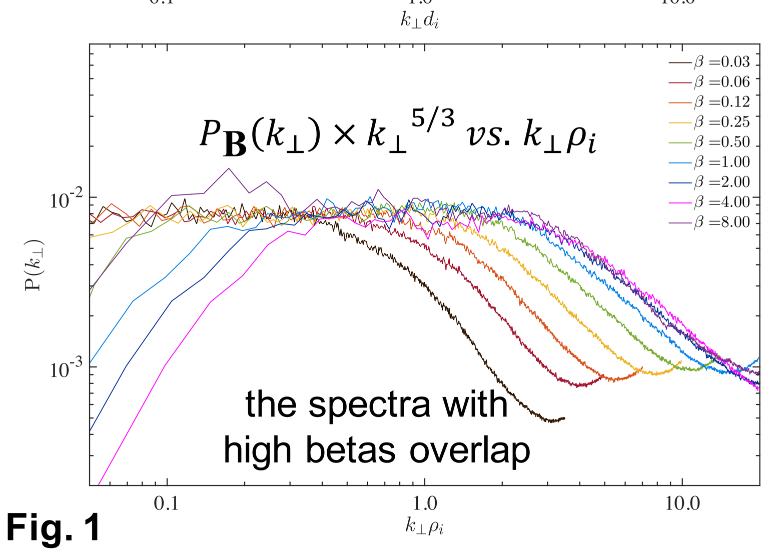


Fig. 1

For all simulations, the spectrum of magnetic fluctuations exhibits two power-law ranges separated by an ion-scales break. The spectral index in the inertial range, α_1, is always $\sim -5/3$, while in the kinetic range, α_2, varies with β. The shape of the spectrum around ion-scales is different with β: a smoother transition for small values and a sharper break for high ones. The position of this transition also depends on β. The values of α_1, α_2, and the scale of the break are listed in the table. The spectra for low β tend to overlap if the x-axis is $k_\perp d_i$, while the spectra for high β tend to overlap if the x-axis is $k_\perp \rho_i$ **[Fig. 1]**.

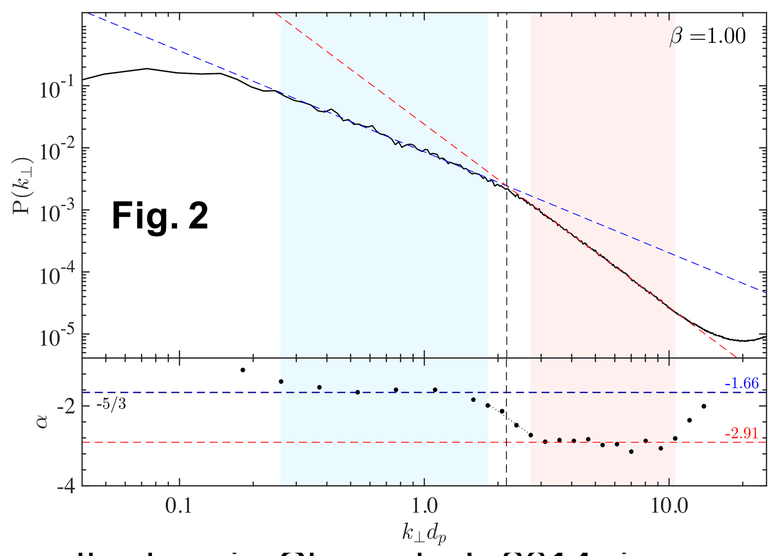


Fig. 2

For each simulation, we identified the break by using the same method as in Chen et al. 2014, i.e., we computed the local power-law fit, α, of the magnetic field spectrum over small intervals and we defined the scale of the break as the wavevector at which α takes a value half way between α_1 and α_2 **[Fig. 2]**.

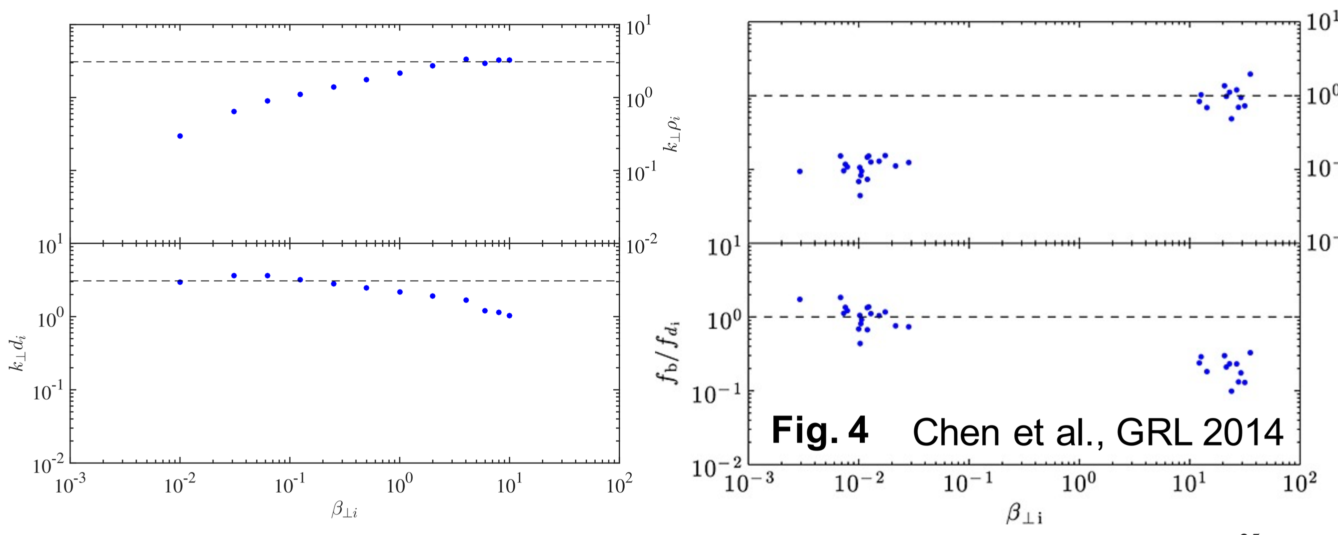


Fig. 4 Chen et al., GRL 2014

The scale of the break is proportional to the ion inertial length, d_i, for $\beta \ll 1$ and to the ion gyroradius, ρ_i, for $\beta \gg 1$ **[Fig. 2]**, consistently with solar wind observations **[Fig. 4]**. For intermediate cases, $\beta \sim 1$, a combination of the two better reproduce the behavior.

We have looked for an empirical relation that could properly reproduce the dependence of the length scale associated to the ion-scale spectral break on the plasma beta, $l^b = l(\beta)$, over the the whole range of investigated values. We found that

$$l^b = 2\left(d_i + \rho_i - \frac{\sqrt{d_i \rho_i}}{2}\right) = 2\, d_i \left(1 + \beta_\perp^{1/2} - \frac{\beta_\perp^{1/4}}{2}\right)$$

meets all the requirements: it is dimensionally correct, it approaches the asymptotic values $2d_i$ and $2\rho_i$ for $\beta \ll 1$ and $\beta \gg 1$, respectively, and it recovers $3d_i \equiv 3\rho_i$ for $\beta = 1$ **[Fig. 5]**. It seems to represent a good approximation for $\beta \in$ [0.01, 10].

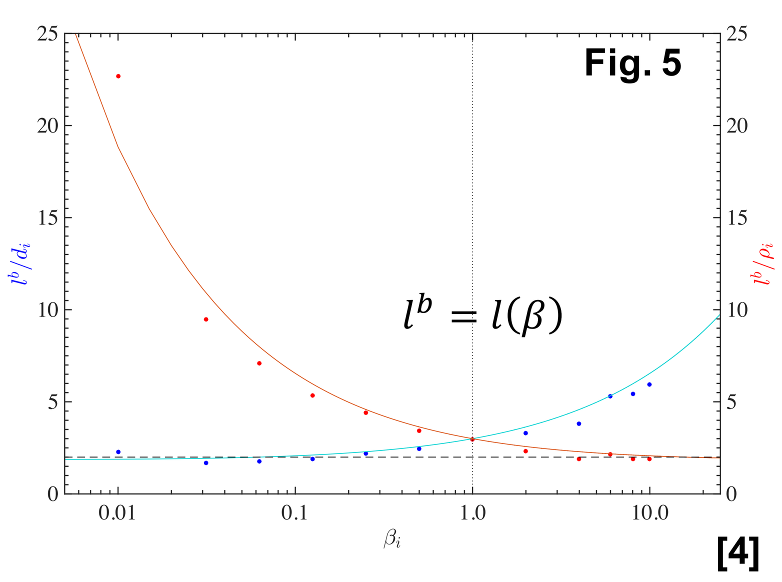


Fig. 5

[4]

DISCUSSION

Our results are in agreement with observations of solar wind turbulence at high and low beta, which shows a clear correlation of the ion-scale spectral break with the larger of the two scales in both limits [Chen et al., GRL 2014]. As possible mechanisms causing the break In our spectra we can exclude the electron Landau damping, due to the use of the hybrid model, while the cyclotron damping is not likely to be quite a relevant process, since our setting is two-dimensional and a significant contribution of $k_\parallel$ is inhibited. In the high-beta regime, the break could be related to the presence of kinetic Alfvén waves. In this limit, the scale at which the Alfvén turbulence becomes dispersive at the transition to kinetic Alfvén turbulence is expected to be ρ_i. In the low-beta regime, the break could be mainly due to dissipation occurring in reconnecting current sheets. Indeed, we observe many current sheets forming around and between coherent structures, and later disrupting because reconnection occurs. If this process was the main responsible for the steepening of the magnetic field spectrum around ion scales, the length scale of the break would be related to the width of current sheets [Leamon et al., ApJ 2000]. This explanation would agree with solar wind observations, which indicate that such width, although variable, shows a good scaling with d_i for low βs [Vasquez et al., JGR 2007]. An accurate statistical study about the current sheets thickness would be necessary in order to better investigate its scaling with the plasma beta, and this will be the subject of future work.

References

[1] Franci, Verdini, Matteini, Landi, and Hellinger, ApJ Lett., 804, L39 (2015)
[2] Franci, Landi, Matteini, Verdini, and Hellinger, ApJ, 812(1):21 (2015)
[3] Franci, Hellinger, Matteini, Verdini, and Landi, AIP Conf. Proc., 1720(1) (2016)
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