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Interactive comment on “Isotropy restoration toward high-beta space plasmas” *by* H. Comişel et al.

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Reply to referee comments

Manuscript: Isotropy restoration toward high-beta space plasmas
NPGD 1 1313-1330 2014
H. Comişel, Y. Narita, and U. Motschmann

We thank both Referees for careful reading and thoughtful comments. Their ques-

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tions, suggestions, and criticisms are justified, and they are well taken in the revised manuscript. Here we give our answers to their comments and questions.

Our revised paper has improvements in the analysis of the anisotropy index determined from simulation. From 28 July to 1 August 2014, after submission of our manuscript, we participated at the Asia Oceania Geosciences Society AOGS 2014 meeting in Sapporo, Japan. We had fruitful discussions with the participants there. We identified through the discussion at the meeting that there are different algorithms in analyzing the simulation data and we extended our analysis by applying a low-pass numerical filter to the fluctuating magnetic field. The unfiltered method used in the submitted manuscript is suitable for analyzing the thermal fluctuations or noise while the filtering method is more suited to study the turbulent cascade. The unfiltered method provides the scaling power-law and the filtering method provides new results. The second method was used to compare with observation. Accordingly, we are showing anisotropy evolution using the two different methods and this is a major change in the revision. The novelty in the revised manuscript is mainly section 3, “Results and discussion”, which was divided in three subsections entitled: 3.1 “Two-dimensional spectra”, 3.2 “Anisotropy evolution”, and 3.3 “Search for anisotropy scaling”.

The revised manuscript has been posted as a supplement, where changes in the manuscript are marked in bold fonts.

We uploaded twice the revised manuscript on each referee report.

Referee 1

General Comments

This manuscript is an extension of Narita et al. [2014]. Both this manuscript and that paper describe the use of Cluster spacecraft measurements as well as two-

dimensional hybrid simulations to study the wavevector anisotropy of magnetic turbulence at ion scale wavelengths. Both methods show that the anisotropy is in the sense of $k_{\mathrm{perp}} \gg k_{\|}$, where "perp" and $\|$ refer to directions relative to the background magnetic field, and that the anisotropy is reduced as the plasma beta increases. The new element in this manuscript is that the wavevector anisotropy from the simulations displays a power-law scaling as a function of the plasma beta. There is modest new content here, but substantial rewriting and clarification are necessary before I would regard the manuscript as appropriate for publication.

Specific Comments

<u>Title</u>: The present title is poor. "Wavevector anisotropy of plasma turbulence at ion kinetic scales: Solar wind observations and hybrid simulations" would be much more informative.

- R1.01. We accept Referee's suggestion. We replace "isotropy restoration" by "wavevector anisotropy is reduced".
  Change in the manuscript:
  - Title.
  - Running title: "Wavevector anisotropy"
  - Abstract: sentence 3, "...that the wavevector anisotropy is reduced with increasing values of ion beta."

<u>Overall</u>: The terms beta and plasma beta are not clearly defined. From the beginning it is necessary to state the mathematical definition of this term, define the appropriate

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symbol, and then use this term and its symbol consistently throughout the manuscript. I believe the definition used here is the ion beta, that is, $\beta_\mathrm{i} = 8\pi n_\mathrm{i} k_\mathrm{B} T_\mathrm{i} / B_0\ 2$*, and that symbol should be used uniformly in the text and in the figures.*

- R1.02. Yes, we use the ion beta throughout the manuscript. Our definition is the same as that mentioned by the referee except for the difference in the unit systems. We use the SI unit system for the reason of spacecraft data processing. Definition of our ion beta β_i is therefore

  $$\beta_\mathrm{i} = \frac{2\mu_0 n_\mathrm{i} k_\mathrm{B} T_\mathrm{i}}{{B_0}^2} \tag{1}$$

  where the symbols denote μ_0 the permeability of free space, n_i the ion number density, k_B the Boltzmann constant, T_i the ion temperature, and B_0 the mean magnetic field magnitude.
  Changes in the manuscript:

  - Definition of ion beta has been added (section 1, paragraph 2 including equation 1), “Ion beta is...magnitude.”
  - We use the expression “ion beta” to avoid confusion (not marked in bold fonts.
  - The mathematical symbol β_i is used where appropriate.

1. Introduction: The first sentence should read “Wavevector anisotropy appears in collisionless plasma turbulence whenever a large-scale magnetic field is present.” The first paragraph is a comprehensive statement of relevant papers, but does not describe the conclusions of these papers. To establish the background for the new results

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here, discussion of content of the previous papers must be provided. That discussion should include the result that, in all the simulation papers except Valentini et al. (2010), the wavevector anisotropy corresponds to $k_{\text{perp}} \gg k_{\|}$. Furthermore, it is necessary to discuss the previously published results that particle-in-cell simulations show the wavevector anisotropy of whistler turbulence at electron scale wavelengths decreases with increasing electron beta [Gary et al., 2010; Saito et al., 2010; Chang et al., 2013; Saito and Gary, Phys. Plasmas, Vol. 19, 012312 (2012) should also be cited.].

- R1.03a. The first sentence. Done.
  Change in the manuscript:
  - Section 1, sentence 1.
- R1.03b. The first paragraph. Yes, we agree that it is informative that the manuscript begins with the conclusions of earlier studies on the anisotropy, not simply mentioning what astrophysical systems show plasma turbulence. We have inserted the following sentences:
  "All these studies conclude that plasma turbulence is primarily anisotropic such that the energy spectrum is extended preferentially in the perpendicular direction to the mean magnetic field, or equivalently, the spatial correlation of the fluctuating magnetic fields decays rapidly in that direction. The perpendicular extension of the spectrum indicates that the spectral energy transfer or cascade is anisotropic accordingly. There are spacecraft observations of the parallel extension of the energy spectrum, but only under limited conditions, e.g., high-speed solar wind streams (Dasso et al., 2005) or shock-upstream region (Narita and Glassmeier, 2010)."
  Change in the manuscript:
  - Section 1, "All these... Glassmeier, 2010)."

- Reference to Dasso, S., Milano, L. J., Matthaeus, W. H., and Smith, C. W.: Anisotropy in fast and slow solar wind fluctuations, Astrophys. J., 635, L181, 2005.
- Reference to Narita, Y. and Glassmeier, K.-H.: Anisotropy evolution of magnetic field fluctuation through the bow shock, Earth Planets Space, 62, e1–e4, 2010.
- Reference to Saito, S., Gary, S. P., Li, H., and Narita, Y.: Whistler turbulence: Particle-in-cell simulations, Phys. Plasmas, 15, 102305, doi:10.1063/1.2997339, 2008.
- Saito, S. and Gary, S. P.: Beta dependence of electron heating in decaying whistler turbulence: Particle-in-cell simulations, Phys. Plasmas, 19, 012312, doi:10.1063/1.3676155, 2012.

- R1.03c. Whistler turbulence papers. This is a good suggestion. Indeed, beta dependence was already presented for whistler turbulence, so these papers must be cited in a proper context. We arranged the sentences.
  Change in the manuscript:
  - Section 1, sentences “Evidence of anisotropy in plasma turbulence has also been presented in numerical simulations using different schemes for plasma dynamics on various spatial scales from the magnetohydrodynamic (MHD) regime to the ion kinetic regime, and down to electron kinetic regime. Most of numerical simulation studies show the perpendicular extension of the spectrum on those scales: magnetohydrodynamic turbulence (Shebalin et al., 1983; Matthaeus et al., 1996; Matthaeus and Gosh, 1999), ion-kinetic turbulence (Valentini et al., 2010; Verscharen et al., 2012; Comişel et al., 2013), gyrokinetic treatment (Howes et al., 2011), and whistler turbulence on electron scales (Saito et al., 2008). Furthermore, particle-in-cell simulations show the wavevector anisotropy of whistler turbulence at

electron-scale wavelengths decreases with increasing electron beta (Gary et al., 2010; Saito et al., 2010; Saito and Gary, 2012; Chang et al., 2013), which motivates our study here."

2.1 Multi-spacecraft measurements: The observed values of $T_\mathrm{e}/T_\mathrm{i}$ should also be stated in Table 1, because the turbulence simulations of Valentini et al. (2010) indicate that the wavevector anisotropy is also a function of this parameter.

- R1.04. The electron-to-ion temperature ratio has been added to Table 1. We include two additional tests for the possible relation with the anisotropy. One is the effect of the electron-to-ion temperature, and the other is the effect of the magnetic field magnitude (suggested by Referee 2). Fig. 8 shows the plot of the anisotropy as a function of the temperature ratio derived from the Cluster spacecraft measurements, but we could not find any clear trend, though the data point at the smallest anisotropy value at $(T_\mathrm{e}/T_\mathrm{i}, A) \simeq (0.7, 1.8)$ could be a sign of the temperature-ratio dependence as indicated by Valentini et al. (2010).
  Changes in the manuscript:
  - Electron-to-ion temperature ratio $T_\mathrm{e}/T_\mathrm{i}$ in Table 1.
  - Figure 8.
  - Section 3.3, paragraph 5 (or the second paragraph from bottom), "For the spacecraft measurements, two additional tests for possible relation with the wavevector anisotropy have been conducted: (1) effect of the electron-to-ion temperature ratio and (2) effect of the magnetic field magnitude. Fig. 8 shows the plot of the anisotropy as a function of the temperature ratio derived from the Cluster spacecraft measurements (for the test 1). Data set

includes that used in our previous paper (NCM14). Due to large variation of anisotropy around the temperature ratio about 0.35, no clear trend or organization can be confirmed about the possible relationship between the anisotropy and the temperature ratio. However, the data point at the smallest anisotropy value at $(T_\mathrm{e}/T_\mathrm{i}, A) \simeq (0.7, 1.8)$ could be a sign of the temperature-ratio dependence as indicated by Valentini et al. (2010)."

<u>2.2 Direct numerical simulation</u>: As a supplement to Figure 3, it would be informative to plot the A factor as a function of time in the simulations. Fig. 3 of Chang et al. (2013) shows that the asymptotic state of whistler turbulence anisotropy is reached more quickly at higher β_e; is the same true for the Alfvenic turbulence simulated here?

- R1.05. The answer is given in the additional changes of the manuscript provided at the end of our reply (section 3.2 below).

<u>3. Results and discussion</u>: The third paragraph is generally wordy and unclear and needs to be rewritten. "The anisotropy index plotted...(Fig. 3) shows a monotonic trend toward reduced anisotropy with increasing β_i." Delete the sentence beginning "The wavevector anisotropy from the simulations..." Delete the phrase "law of anisotropy as" and the sentence "Namely, the slope value is close to -0.3." In line 12, replace "the scaling law explains" with "Equation (2) represents".

- R1.06. We thank the constructive suggestions here and in the following comments.
  The suggestions are taken in the new paragraph 3 of section 3.3.

The fourth paragraph ("What is the reason...") is not useful and should be deleted. Particle velocities in the simulations are in full three dimensions, so that the statement "motion around the large-scale magnetic field is forbidden" is simply wrong. The remainder of the paragraph is unclear and vague (What is a "non-eddy spatial structure"?) and does not contribute to the physical understanding. Delete the whole paragraph.

- R1.07. Done.

<u>4. Conclusions</u>: "Our observational and computational studies extend the results of NCM14, providing additional evidence that the wavevector anisotropy of plasma turbulence at ion-scale wavelengths becomes weaker with increasing $\beta_{\rm i}$. Furthermore, our two-dimensional hybrid simulations provide a new power-law scaling relation between the wavevector anisotropy and $\beta_{\rm i}$. This fact, however, should not be taken..."

- R1.08. Done.
  Change in the manuscript:
  - Section 4, paragraph 1, "Our observational and computational ... with increasing $\beta_{\rm i}$." The following sentence "Furtheremore, our two-dimensional ..." was modified and moved in the next paragraph (please see below).

Technical Corrections

Page 1320, line 22 (Section 3, first paragraph): "lager" should be "larger".

Page 1323, line 16 (Section 4, third paragraph): "logics" should be "logic".

- R1.09. Done.
  Changes in the manuscript:
    - Section 3.1, paragraph 1, sentence 4, "larger"
    - Section 4, paragraph 3, sentence 1, "logic"

Further changes in the manuscript are provided below.

- Abstract
    - sentence 4, we added "of the fluctuating magnetic field that is controlled by the thermal or hybrid particle in cell simulation noise. Likewise, there is a weak evidence that the power-law scaling can be extended to the turbulent fluctuating cascade."
- Section 2.1
    - Last paragraph, last sentence: Fig. 3 is now Fig. 6.
- Section 2.2
    - last paragraph, first sentence: we added "or even at later time" and "or by introducing new runs.".

  - last paragraph, sentence 2: The expression “This represents the longest possible simulation run” was changed with “This represents a long simulation run”.
  - last paragraph: After sentence 3, a new sentence was introduced: “New runs have been additionally carried out in order to evaluate the range of variation of the anisotropy in respect with some simulation parameters e.g. grid grid resolution or the number of super-particles.”
  - last paragraph: The last sentence “The anisotropy-beta relation is displayed in Fig. 3.” was replaced by “In the next section, the anisotropy-time evolution is shown in Figs. 3, 4, and 5, while the anisotropy-beta relation is displayed in Fig. 6 and Fig. 7.”

- Section 3
  Section 3 was reorganized in three subsections: 3.1 Two-dimensional spectra, 3.2 Anisotropy evolution, and 3.3 Search for anisotropy scaling.

- Section 3.1 is composed from the first two paragraphs of the former section 3, with the following changes:

  - First paragraph: The last two sentences of the former paragraph were moved to the first paragraph of section 3.3.
  - Second paragraph: The last sentence of the former paragraph was deleted.

- Section 3.2 includes the answer R1.05.

  - Paragraph 1: “The anisotropy index was initially determined from simulation in the wavenumber range $0.3 < \frac{kV_\mathrm{A}}{\Omega_\mathrm{p}} < 6$. The obtained anisotropy is plotted as a function of time in Fig. 3. After the sudden increase at the earliest time, the anisotropy index reaches a saturation level in less than 15 ion gyroperiods without crossing the evolution curves at the other values of ion beta throughout the simulation runs until 2000 ion gyroperiods. The exception is the case at the smallest value of ion beta ($\beta_\mathrm{i} = 0.05$) that the anisotropy index increases and peaks at about 500 ion gyroperiods, and then decreases. The beta dependence that the anisotropy is reduced with increasing ion beta can been seen even in the early evolution phase around a few ion gyroperiods. Furthermore, the anisotropy index at ion beta 0.05 turns back at later times (t$\Omega_p >$ 1500). Could be this peculiar evolution due to the thermal fluctuations, see e.g. Yoon et al.(2014), or due to the numerical noise of the hybrid PIC simulation, see e.g. Jenkins and Lee (2007), is a question we cannot answer in this paper. Nevertheless, there is no connection with the initial Alfvénic excitation imposed at the start of the simulation."

- Paragraph 2: "We found that the fast saturation of the anisotropy at the initial time is a consequence of the contribution of high wavenumber terms of the power spectrum. By using a low-pass filter in the fluctuating magnetic field, the quick saturation of the anisotropy at the initial time is removed. The higher the ion beta value is, the lower the cutoff wavenumber (k_cut) has to be employed. The effect of filtering the fluctuating magnetic field spectrum is demonstrated in Fig. 4 for ion beta 0.05, 0.1, 0.2, and in Fig. 5 for ion beta 0.5, 1, and 2. The cutoff wavenumber was $k_\mathrm{cut}\frac{V_\mathrm{A}}{\Omega_\mathrm{p}}$=3 and $k_\mathrm{cut}\frac{V_\mathrm{A}}{\Omega_\mathrm{p}}$=1, respectively."
- Paragraph 3: " The anisotropy index starts to increase abruptly and attends a peak value around $t\Omega_p \approx 500$ at ion beta 0.05 while for ion beta 0.1 and 0.2 the growing is slow and the crests are at $t\Omega_p \approx 1000$ and $t\Omega_p \approx 1700$, respectively. At larger ion beta values, the anisotropy index evolves smoothly and extends to a saturation level after time 500 ion gyroperiods. The anisotropy index is decreasing with the increasing of ion beta as in the previous evaluation excepting ion beta 0.5."

- Paragraph 4: “ The reduced anisotropy with increasing beta was already pointed out from the particle-in-cell simulations Chang et al.(2013) for whistler turbulence on electron kinetic scales. Our result confirms this tendency even on the ion kinetic scales. We note however that the peaks of the anisotropy at the low ion beta values evolve different than those from Chang et al.(2013). In our plots (Fig. 4), the peak is achieved quicker at lower ion beta values, while in the PIC simulation, a reversed dependence with electron beta is observed.”

- Section 3.3
  - First paragraph: New sentence 1: “The experimental anisotropy index is plotted as a function of ion beta at once with the latter values obtained from simulation (filtered data) in Fig. 6.”
  - First paragraph: New last sentence: “The results from simulation were obtained by averaging the time dependent anisotropies shown in Fig. 4 and Fig. 5 as 6.9 (at ion beta 0.05), 3.2 (at ion beta 0.1), 1.9 (at ion beta 0.2), 1.5 (at ion beta 0.5), 1.9 (at ion beta 1.0), and 1.7 (at ion beta 2.0).”
  - The paragraph 2 is given by the sentences 2, 3, and 4 from the paragraph 3 of former section 3, and the following new sentences: “In the simulation, the anisotropy falls down steeper at low ion beta (at 0.05, 0.1 and 0.2) and then decreases smoothly at higher β_i (1, 2). This is similarly with the tendency observed in the solar wind if the shift in ion beta is disregarded.”
  - The paragraph 3 is a new paragraph containing the power-law scaling described in the former section 3: “The beta dependence of the anisotropy determined from the unfiltered data is given separately in Fig. 7. It clearly shows a monotonic descending trend that exhibits a power-law scaling in the form $A \propto \beta_{\mathrm{i}}^{-\alpha}$. The slope in the scaling can be determined by the fitting

procedure, and we obtain the empirical scaling

$$A = 2.035 \times \beta_{\mathrm{i}}^{-0.295} \tag{2}$$

Eq. (4) represents with small deviations the anisotropy index controlled by the thermal or by the hybrid particle in cell (PIC) simulation noise. Dieckmann et al.(2004) studied the noise spectra of electrostatic waves in an unmagnetized electron plasma by particle in cell (PIC) simulations. The purpose of their work was to find out the interplay between three categories of noise: thermal, numerical and PIC simulation noise. Their results show that at smaller wavenumbers the estimated numerical noise dominates the simulation noise, while at large values near the Nyquest wavenumber, the thermal noise becomes more effective. We repeated the simulations for short times ($t\Omega_p < 200$) by varying the number of super-particles, and therefore, by changing the numerical noise amplitude, another set of anisotropy indices was determined. An additional anisotropy index extends our study at higher values of ion beta ($\beta_i = 4$). This numerical experiment brings evidence that the anisotropy power-law scaling from Eq. 4 is linked to thermal rather than to numerical noise. The power-law dependence is added in Fig. 6. The anisotropy index of the simulated turbulent cascade follows the power-law in the limit of the error bars."

- Section 4 Conclusions

  - The second sentence of the first paragraph, "Furthermore, our two-dimensional ..." was changed and moved in the second paragraph: "Furthermore, our two-dimensional hybrid simulations show that a power-law scaling relation between the wavevector anisotropy and β_{i} could exist. The power-law function was found to describe accurately the anisotropy index driven by the thermal or hybrid PIC - simulation noise."

- Same paragraph, we changed “theoretical studies” with “theoretical and computational studies”.

- References
  We added the following references:
  - Reference to Yoon, P.H., Schlickeiser, R., and Kolberg, U.: Thermal fluctuation levels of magnetic and electric fields in unmagnetized plasma: The rigorous relativistic kinetic theory, Phys. Plasmas, 21, 032109, doi:10.1063/1.4868232, 2014.
  - Reference to Jenkins, T. G., and Lee, W. W.: Fluctuations of discrete particle noise in gyrokinetic simulation of drift waves, Phys. Plasmas, 14, 032307, doi:10.1063/1.2710808, 2007.
  - Reference to Dieckmann, M. E., Ynnerman, A., Chapman, S. C, Rowlands, G., and Andersson, N.: Simulating thermal noise, Physica Scripta, 69, 456–460, doi:10.1238/Physica.Regular.069a00456, 2004.

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tions, suggestions, and criticisms are justified, and they are well taken in the revised manuscript. Here we give our answers to their comments and questions.

Our revised paper has improvements in the analysis of the anisotropy index determined from simulation. From 28 July to 1 August 2014, after submission of our manuscript, we participated at the Asia Oceania Geosciences Society AOGS 2014 meeting in Sapporo, Japan. We had fruitful discussions with the participants there. We identified through the discussion at the meeting that there are different algorithms in analyzing the simulation data and we extended our analysis by applying a low-pass numerical filter to the fluctuating magnetic field. The unfiltered method used in the submitted manuscript is suitable for analyzing the thermal fluctuations or noise while the filtering method is more suited to study the turbulent cascade. The unfiltered method provides the scaling power-law and the filtering method provides new results. The second method was used to compare with observation. Accordingly, we are showing anisotropy evolution using the two different methods and this is a major change in the revision. The novelty in the revised manuscript is mainly section 3, “Results and discussion”, which was divided in three subsections entitled: 3.1 “Two-dimensional spectra”, 3.2 “Anisotropy evolution”, and 3.3 “Search for anisotropy scaling”.

The revised manuscript has been posted as a supplement, where changes in the manuscript are marked in bold fonts.

We uploaded twice the revised manuscript on each referee report.

Referee 2

General Comments

The manuscript presents the studies on the dependence of the anisotropy on plasma beta employing Cluster data and hybrid simulations. The anisotropy is found to de-

crease with plasma beta as a power law. The power law dependence is a new results and is publishable.

Specific Comments

1. In the second paragraph of the introduction, it is mentioned that plasma beta is the primary control parameter for the anisotropy. It means that anisotropy is either independent of or weakly dependent on other plasma parameters. The results do show variation of anisotropy with plasma beta but it does not necessarily mean that the plasma beta is the only parameter controlling the anisotropy.

- R2.01. Right. It is certainly possible that other variables or parameters influence the anisotropy. We use the phrase "one of the control parameters" in the introduction.
  Change in the manuscript:
  - Section 1, sentence 1, "one of the control parameters"

It is known that anisotropy depends on the strength of large scale magnetic field [Dastgeer and Zank, The Astrophysical Journal, 599:715-722, 2003]. So it is expected that it would depend on plasma beta $\propto 1/B^2$ *as well. So is the dependence of anisotropy on plasma beta coming from the dependence on magnetic field only or the pressure also influences the anisotropy?*

- R2.02. We have checked two possible parameters in search of possible relationship to anisotropy: the electron-to-ion temperature ratio (test 1, already mentioned in the reply to Referee 1, R1.04) and the magnetic field magnitude (test 2). The test 2 was made using the spacecraft data only, since the magnetic field magnitude is used as a normalization factor in the simulations to scale the other

quantities such as the gyrofrequency. In other words, ion beta dependence was studied in the simulations by changing the temperature. We confirm the possible effect of magnetic field magnitude qualitatively. But quantitatively, the scaling $A \propto B_0^2$ predicted by Dastgeer and Zank (2003) gives a steeper anisotropy curve than the measured one.
Changes in the manuscript:

- Figure 9.
- Section 3.3, paragraph 5 (last paragraph), "Fig. 9 shows the plot of the anisotropy index as a function of the mean magnetic field magnitude derived from the Cluster data analysis (for the test 2). There is a weak tendency that the anisotropy is stronger with increasing magnetic field magnitude. In electron magnetohydrodynamics it is known that anisotropy depends on the strength of large-scale magnetic field (Dastgeer and Zank, 2003) as

  $$A \propto B_0^2. \tag{1}$$

  In their paper, the anisotropy quantity (the symbol R was used) is related to our definition of the anisotropy index by $R = A^{-2}$. This scaling is verified using our anisotropy measurements using Cluster spacecraft data. Comparison with the numerical simulation data is not possible here, since the magnetic field is normalized to unity and the thermal pressure is varied in the simulations. The measured slope shows the same tendency as that derived by Dastgeer and Zank (2003), but it is flatter than the scaling B_0^2. We interpret that the dependence of anisotropy on ion beta comes partly from the magnetic field magnitude and partly from the plasma thermal pressure."
- Reference to Dastgeer, S., and Zank, G. P.: Anisotropic turbulence in two-dimensional electron magnetohydrodynamics, Astrophys. J., 599, 715–722, doi:10.1086/379225, 2003.

2. It would be useful to clarify in some more detail how 2-D spectra in $k_\perp$-$k_\parallel$ space was obtained from 4-D spectra in wave-vector frequency domain obtained from Cluster observations. The 2-D spectra in the simulations is in k_y-$k_\parallel$ space while in the observations it is in $k_\perp$-$k_\parallel$ space, where $k_\perp = \sqrt{k_\mathrm{y}^2 + k_\mathrm{x}^2}$. How do the two 2-D spectra correspond to each other.

- R2.03a. The reduction was made through the integration over the frequencies ω and then over the azimuthal angles ϕ around the mean magnetic field.

  $$E^{(\mathrm{2D})}(k_\perp, k_\parallel) = \int \mathrm{d}\phi \int \mathrm{d}\omega\, E^{(\mathrm{4D})}(k_\perp, k_\parallel, \phi, \omega). \tag{2}$$

  The perpendicular components of wavevectors therefore represent the magnitude, not in any specific direction.
  Change in the manuscript:

  - Section 2.1, paragraph 3, “The reduction... specific direction.”

- R2.03b. The perpendicular wavevector components in the two-dimensional spectra for the simulation data are chosen in the direction within the simulation plane.
  Change in the manuscript:

  - Section 2.2, paragraph 6, “The perpendicular wavevector... simulation plane.”

Further changes in the manuscript are provided below.

- Abstract

  - sentence 4, we added at the end of this sentence, “of the fluctuating magnetic field that is controlled by the thermal or hybrid particle in cell simulation noise. Likewise, there is a weak evidence that the power-law scaling can be extended to the turbulent fluctuating cascade.”

- Section 2.1

  - Last paragraph, last sentence: Fig. 3 is now Fig. 6.

- Section 2.2

  - last paragraph, first sentence: we added “or even at later time” and “or by introducing new runs.”.
  - last paragraph, sentence 2: The expression “This represents the longest possible simulation run” was changed with “This represents a long simulation run”.
  - last paragraph: After sentence 3, a new sentence was introduced: “New runs have been additionally carried out in order to evaluate the range of variation of the anisotropy in respect with some simulation parameters e.g. grid grid resolution or the number of super-particles.”
  - last paragraph: The last sentence “The anisotropy-beta relation is displayed in Fig. 3.” was replaced by “In the next section, the anisotropy-time evolution is shown in Figs. 3, 4, and 5, while the anisotropy-beta relation is displayed in Fig. 6 and Fig. 7.”

- Section 3
  Section 3 was reorganized in three subsections: 3.1 Two-dimensional spectra, 3.2 Anisotropy evolution, and 3.3 Search for anisotropy scaling.

- Section 3.1 is composed from the first two paragraphs of the former section 3, with the following changes:
    - First paragraph: The last two sentences of the former paragraph were moved to the first paragraph of section 3.3.
    - Second paragraph: The last sentence of the former paragraph was deleted.
- Section 3.2 includes the answer R1.05 for Referee 1.
    - Paragraph 1: “The anisotropy index was initially determined from simulation in the wavenumber range $0.3 < \frac{kV_\mathrm{A}}{\Omega_\mathrm{p}} < 6$. The obtained anisotropy is plotted as a function of time in Fig. 3. After the sudden increase at the earliest time, the anisotropy index reaches a saturation level in less than 15 ion gyroperiods without crossing the evolution curves at the other values of ion beta throughout the simulation runs until 2000 ion gyroperiods. The exception is the case at the smallest value of ion beta ($\beta_\mathrm{i} = 0.05$) that the anisotropy index increases and peaks at about 500 ion gyroperiods, and then decreases. The beta dependence that the anisotropy is reduced with increasing ion beta can been seen even in the early evolution phase around a few ion gyroperiods. Furthermore, the anisotropy index at ion beta 0.05 turns back at later times (t$\Omega_p >$ 1500). Could be this peculiar evolution due to the thermal fluctuations, see e.g. Yoon et al.(2014), or due to the numerical noise of the hybrid PIC simulation, see e.g. Jenkins and Lee (2007), is a question we cannot answer in this paper. Nevertheless, there is no connection with the initial Alfvénic excitation imposed at the start of the simulation.”
    - Paragraph 2: “We found that the fast saturation of the anisotropy at the initial time is a consequence of the contribution of high wavenumber terms of the power spectrum. By using a low-pass filter in the fluctuating magnetic field,

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the quick saturation of the anisotropy at the initial time is removed. The higher the ion beta value is, the lower the cutoff wavenumber ($k_{\rm cut}$) has to be employed. The effect of filtering the fluctuating magnetic field spectrum is demonstrated in Fig. 4 for ion beta 0.05, 0.1, 0.2, and in Fig. 5 for ion beta 0.5, 1, and 2. The cutoff wavenumber was $k_{\rm cut}\frac{V_{\rm A}}{\Omega_{\rm p}}$=3 and $k_{\rm cut}\frac{V_{\rm A}}{\Omega_{\rm p}}$=1, respectively."

- Paragraph 3: " The anisotropy index starts to increase abruptly and attends a peak value around $t\Omega_p \approx 500$ at ion beta 0.05 while for ion beta 0.1 and 0.2 the growing is slow and the crests are at $t\Omega_p \approx 1000$ and $t\Omega_p \approx 1700$, respectively. At larger ion beta values, the anisotropy index evolves smoothly and extends to a saturation level after time 500 ion gyroperiods. The anisotropy index is decreasing with the increasing of ion beta as in the previous evaluation excepting ion beta 0.5."
- Paragraph 4: " The reduced anisotropy with increasing beta was already pointed out from the particle-in-cell simulations Chang et al.(2013) for whistler turbulence on electron kinetic scales. Our result confirms this tendency even on the ion kinetic scales. We note however that the peaks of the anisotropy at the low ion beta values evolve different than those from Chang et al.(2013). In our plots (Fig. 4), the peak is achieved quicker at lower ion beta values, while in the PIC simulation, a reversed dependence with electron beta is observed."

- Section 3.3
  - First paragraph: New sentence 1: "The experimental anisotropy index is plotted as a function of ion beta at once with the latter values obtained from simulation (filtered data) in Fig. 6."
  - First paragraph: New last sentence: "The results from simulation were obtained by averaging the time dependent anisotropies shown in Fig. 4 and

Fig. 5 as 6.9 (at ion beta 0.05), 3.2 (at ion beta 0.1), 1.9 (at ion beta 0.2), 1.5 (at ion beta 0.5), 1.9 (at ion beta 1.0), and 1.7 (at ion beta 2.0)."

- The paragraph 2 is given by the sentences 2, 3, and 4 from the paragraph 3 of former section 3, and the following new sentences: "In the simulation, the anisotropy falls down steeper at low ion beta (at 0.05, 0.1 and 0.2) and then decreases smoothly at higher β_i (1, 2). This is similarly with the tendency observed in the solar wind if the shift in ion beta is disregarded."
- The paragraph 3 is a new paragraph containing the power-law scaling described in the former section 3: "The beta dependence of the anisotropy determined from the unfiltered data is given separately in Fig. 7. It clearly shows a monotonic descending trend that exhibits a power-law scaling in the form $A \propto \beta_\mathrm{i}^{-\alpha}$. The slope in the scaling can be determined by the fitting procedure, and we obtain the empirical scaling

$$A = 2.035 \times \beta_\mathrm{i}^{-0.295} \tag{3}$$

Eq. (4) represents with small deviations the anisotropy index controlled by the thermal or by the hybrid particle in cell (PIC) simulation noise. Dieckmann et al.(2004) studied the noise spectra of electrostatic waves in an unmagnetized electron plasma by particle in cell (PIC) simulations. The purpose of their work was to find out the interplay between three categories of noise: thermal, numerical and PIC simulation noise. Their results show that at smaller wavenumbers the estimated numerical noise dominates the simulation noise, while at large values near the Nyquest wavenumber, the thermal noise becomes more effective. We repeated the simulations for short times ($t\Omega_p < 200$) by varying the number of super-particles, and therefore, by changing the numerical noise amplitude, another set of anisotropy indices was determined. An additional anisotropy index extends our study at higher values of ion beta ($\beta_i = 4$). This numerical experiment brings evidence that the anisotropy power-law scaling from Eq. 4 is linked to thermal rather than to numerical noise. The power-law dependence is added in Fig. 6. The anisotropy index of the simulated turbulent cascade follows the power-law in the limit of the error bars."

- Section 4 Conclusions
  - The second sentence of the first paragraph, "Furthermore, our two-dimensional ..." was changed and moved in the second paragraph: "Furthermore, our two-dimensional hybrid simulations show that a power-law scaling relation between the wavevector anisotropy and β_i could exist. The power-law function was found to describe accurately the anisotropy index driven by the thermal or hybrid PIC - simulation noise."
  - Same paragraph, we changed "theoretical studies" with "theoretical and computational studies".
- References
  We added the following references:
  - Reference to Yoon, P.H., Schlickeiser, R., and Kolberg, U.: Thermal fluctuation levels of magnetic and electric fields in unmagnetized plasma: The rigorous relativistic kinetic theory, Phys. Plasmas, 21, 032109, doi:10.1063/1.4868232, 2014.
  - Reference to Jenkins, T. G., and Lee, W. W.: Fluctuations of discrete particle noise in gyrokinetic simulation of drift waves, Phys. Plasmas, 14, 032307, doi:10.1063/1.2710808, 2007.
  - Reference to Dieckmann, M. E., Ynnerman, A., Chapman, S. C, Rowlands, G., and Andersson, N.: Simulating thermal noise, Physica Scripta, 69, 456–460, doi:10.1238/Physica.Regular.069a00456, 2004.

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