Energy Dissipation in Sheared Magnetic Fields

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Motivation and Objective

- When an Alfven wave propagates in a sheared magnetic field, its wavenumber increases until $k_\perp \rho_i \approx 1$, such that it can efficiently Landau damp.
- These kinetic Alfven waves generated from the spatial cascade of Alfven waves play a crucial role in kinetic turbulence [1].
- Simulations show that in turbulent systems electron heating occurs near current sheets [2].
- We want to clarify the physical reasoning and theory behind why electron heating is stronger near current sheets.

Background

A shear magnetic field generates small scale structures in velocity space, leading to phase mixing, which then causes heating.

Once spatial perturbations reach the scale of the ion Larmor radius ($k_\perp \rho_i \approx 1$), kinetic Alfven modes that play a large role in collisional electron heating become important, generating kinetic Alfven waves.

A fluid model such as RMHD displays singularities at resonant Alfven points, so using a kinetic model which incorporates finite ion Larmor radius effects is needed to resolve the behavior of the plasma at those resonant layers.

Problem Setup

We perform simulations using the spectral code Viriato, which solves the KREHM equations:

$$\frac{1}{n_{0e}} \frac{d\delta n_e}{dt} = -\hat{\boldsymbol{b}} \cdot \nabla \frac{e}{cm_e} d_e^2 \nabla_\perp^2 A_\parallel \quad (1)$$

$$\frac{d}{dt}\left(A_\parallel - d_e^2 \nabla_\perp^2 A_\parallel\right) = \eta \nabla_\perp^2 A_\parallel - c\frac{\partial \varphi}{\partial z} + \frac{cT_{0e}}{e} \hat{\boldsymbol{b}} \cdot \nabla \left(\frac{\delta n_e}{n_{0e}} + \frac{\delta T_{\parallel e}}{T_{0e}}\right) \quad (2)$$

$$\frac{dg_e}{dt} + v_\parallel \hat{\boldsymbol{b}} \cdot \nabla \left(g_e - \frac{\delta T_{\parallel e}}{T_{0e}} F_{0e}\right) = C\left[g_e\right] + \left(1 - \frac{2v_\parallel^2}{v_{\mathrm{the}}^2}\right) F_{0e} \hat{\boldsymbol{b}} \cdot \nabla \frac{e}{cm_e} d_e^2 \nabla_\perp^2 A_\parallel . \quad (3)$$

We start with a uniform plasma in a magnetic field that varies as $\sin(x)$, perturbed by a small-amplitude perturbation of magnetic flux in all directions. The plasma is contained in a periodic box of size $L_x = 2\pi, L_y = 4\pi, L_z = 2\pi$.

Fluid vs Kinetic Model

To compare plasma behavior across the three cases of a fluid RMHD model, a kinetic model without collisions, and a fully kinetic model, we looked at how the current parallel to the strong magnetic guide field evolved in time for each case.

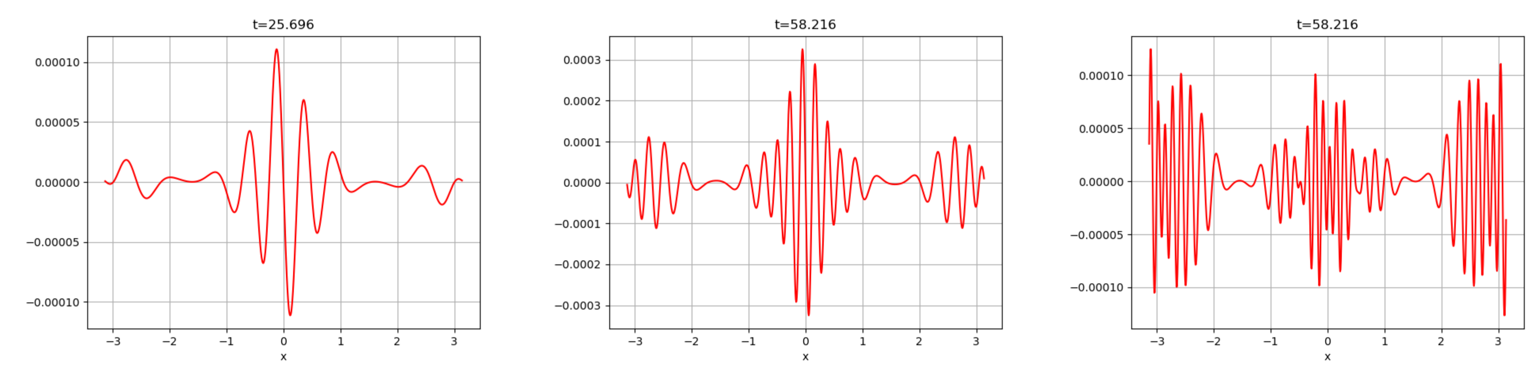

Fig. 1: Fully fluid RMHD model, in which ρ_i, ρ_s, and d_e are all unresolved. Progressively larger amplitude and higher wavenumber structures form around $x = -\pi, 0, \pi$, with no way to damp these oscillations.

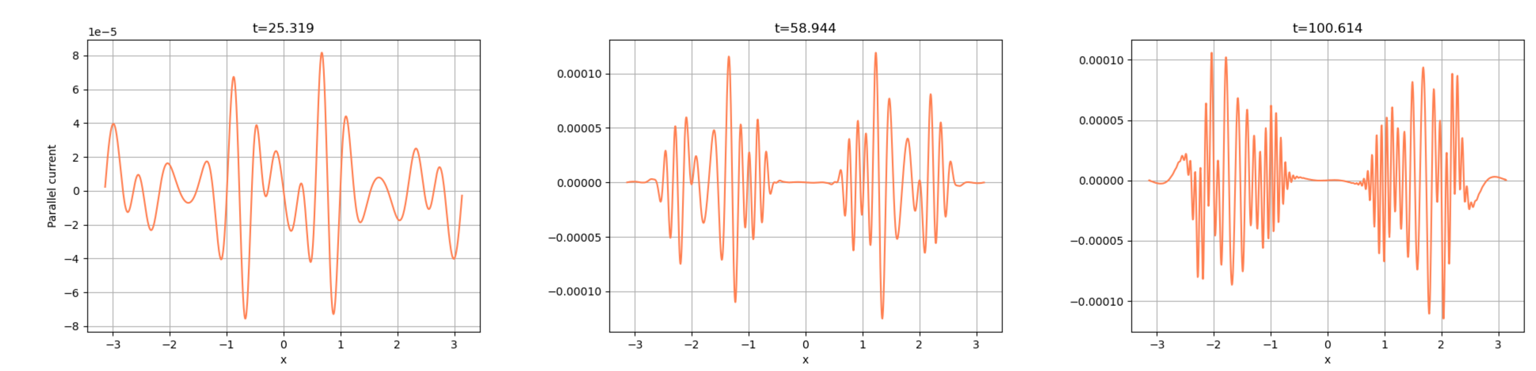

Fig. 2: Kinetic model, in which ρ_i, ρ_s, and d_e are all resolved, but no collisions are allowed. Similar small-scale structures form.

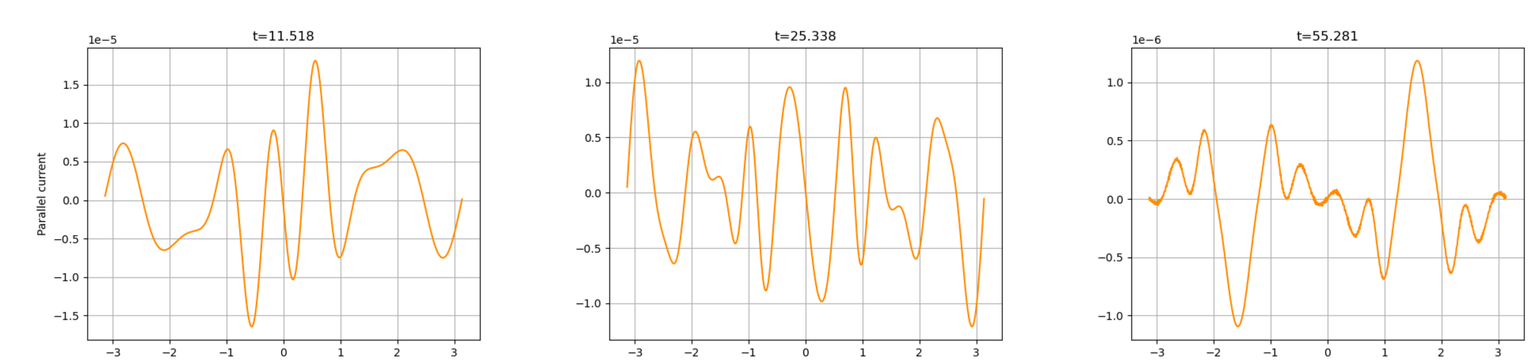

Fig. 3: Kinetic model in which collisions *are* allowed, and so energy is dissipated/oscillations are damped before they reach small scales.

References

[1] Muni Zhou, Zhuo Liu, and Nuno F. Loureiro. *Intermittency and electron heating in kinetic-Alfvén-wave turbulence.* 2022. DOI: 10.48550/ARXIV.2208.02441. URL: https://arxiv.org/abs/2208.02441.

[2] I Furno et al. "Coalescence of two magnetic flux ropes via collisional magnetic reconnection". In: *Physics of Plasmas* 12.5 (2005).

Electron Heating

At positions with large magnetic field gradient (near $x = 0$ since the magnetic field varies as $\sin(x)$), phase mixing leads to generation of kinetic Alfven waves, accompanied by transfer of energy to higher velocity moments. This energy is then dissipated through hyper-collisions, leading to localized electron heating.

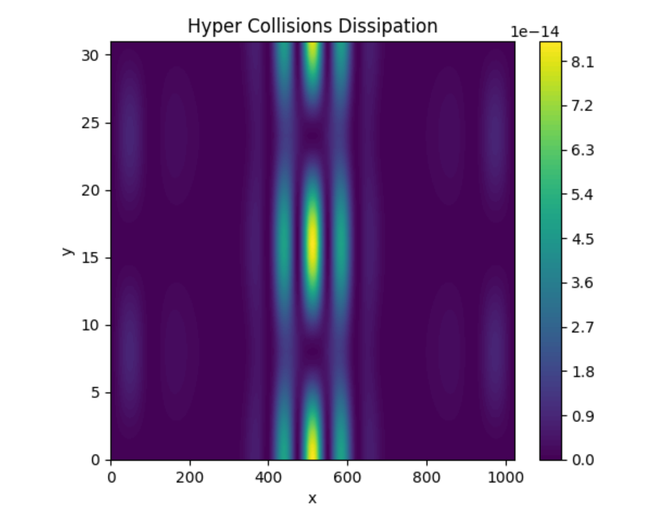

Fig. 4: Energy dissipation is localized near $x = 0$, wher the magnetic field gradient is highest.

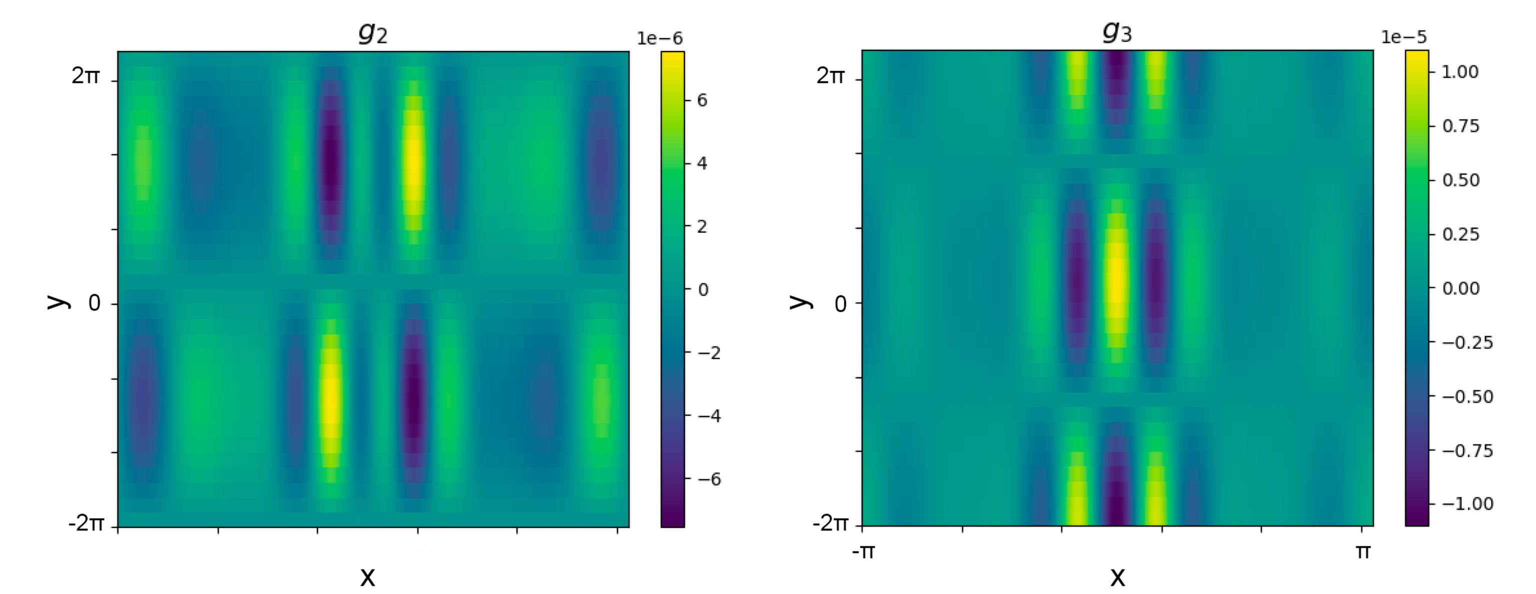

Fig. 5: Amplitude of velocity moments $m = 2$ and $m = 3$ respectively, showing that near $x = 0$, there is a transfer of energy to higher m

Conclusions & Future Work

- In this setup, energy dissipation is localized in regions of high magnetic field gradient, which agrees with past simulations showing that in turbulent systems, electron heating occurs hear current sheets.
- In the future, we need to clarify why Landau damping is occurring around current sheets and causing electron heating, even though there are no small scale structures forming at the scale of ρ_i for the fully kinetic case.
- Ultimately, we'd like to develop a linear/analytical theory for transfer of energy to high velocity moments and a physical reason for why this happens around current sheets.

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