Spontaneous reconnection in three-dimensional particle-in-cell simulations of collisionless plasma turbulence

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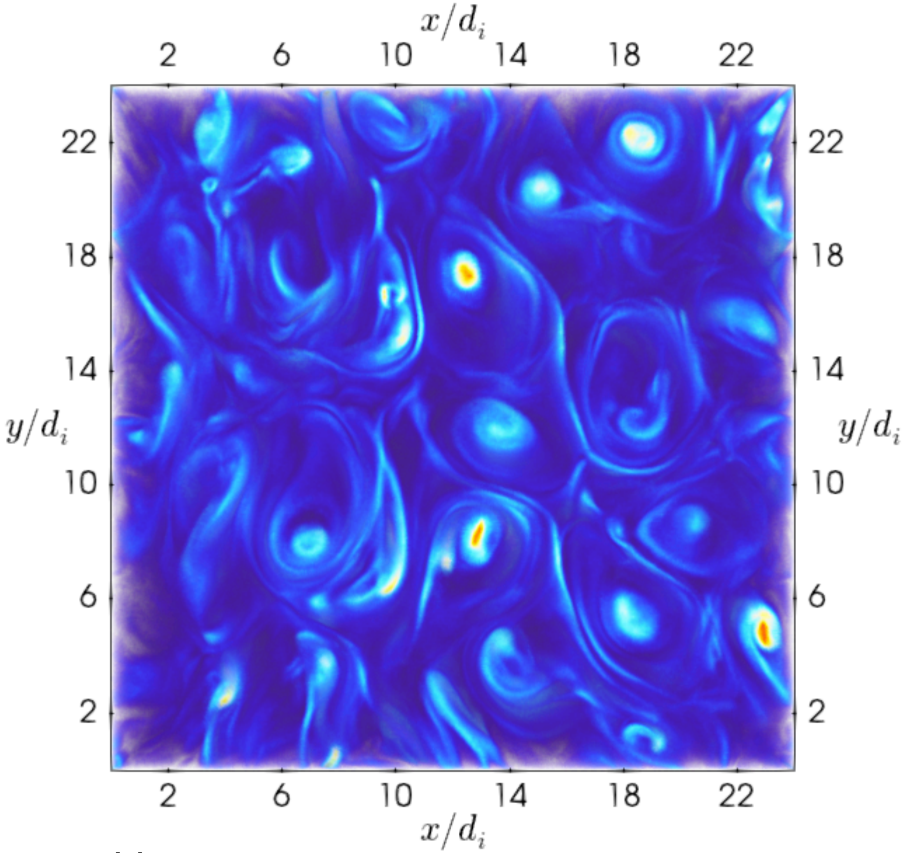
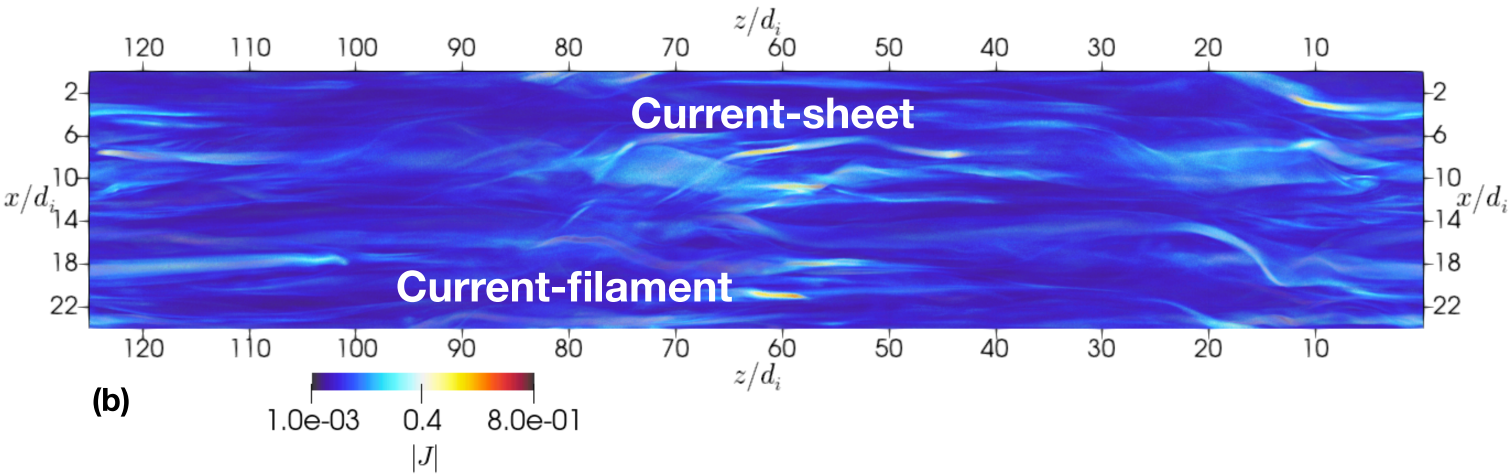


Figure 1: Volume rendering of the current density $|\mathbf{J}|$ in our simulations

Summary

We use 3D fully kinetic particle-in-cell simulations to study the spontaneous formation of magnetic reconnection as a self-consistent component of the turbulent cascade under solar-wind-like conditions. We simulate anisotropic decaying Alfvénic turbulence created by counter-propagating Alfvén waves. The initial wavevector anisotropy is consistent with critical-balance theory. We observe the creation of small-scale current-density structures such as current filaments and current sheets as well as the formation of magnetic flux ropes as part of the turbulent cascade. We develop and apply a new set of indicators to find reconnection regions in 3D particle-in-cell simulations.

We observe the spontaneous creation of reconnection events in the simulation domain and we analyse one of the reconnection events associated with a twisted flux rope in detail. This event is highly dynamic and asymmetric. We study the plasma bulk quantities near and through the reconnection region and find agreement with reconnection exhausts in the solar wind.



Introduction

- The solar wind shows a non-adiabatic temperature profile with distance from the Sun which suggests the presence of local heating and particle-acceleration mechanisms [1]. Turbulence and magnetic reconnection are candidate mechanisms to account for this heating.
- Turbulence is a process in which the energy transforms from large to small spatial and temporal scales. In plasma turbulence, the magnetic field imposes an anisotropy in the energy cascade with respect to the direction of the magnetic field [2]. Observations of magnetic field fluctuations in the solar-wind show anisotropic in a broad range of scales [3].
- Magnetic reconnection is a multiscale process in which particles are heated and accelerated while the magnetic field topology changes [4].
- In this work, we study the formation of electric current structures and the spontaneous onset of 3D magnetic reconnection in particle-in-cell (PIC) simulations of collisionless anisotropic Alfvénic turbulence [5].

Numerical set up

- We use the PIC code Plasma Simulation Code [PSC,6] to simulate anisotropic low-frequency counter-propagating Alfvén waves within an elongated box as shown in Figure 2.
- We consider a background magnetic field $\mathbf{B}_0$ along the z-axis and we use periodic boundary conditions. The volume of the box is $24 \times 24 \times 125 d_i^3$ where d_i is the ion inertial length. For details about the simulation see (Agudelo et al., JPP, submitted 2020).

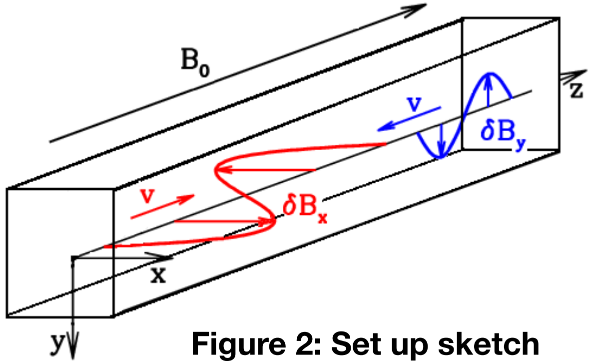


Figure 2: Set up sketch

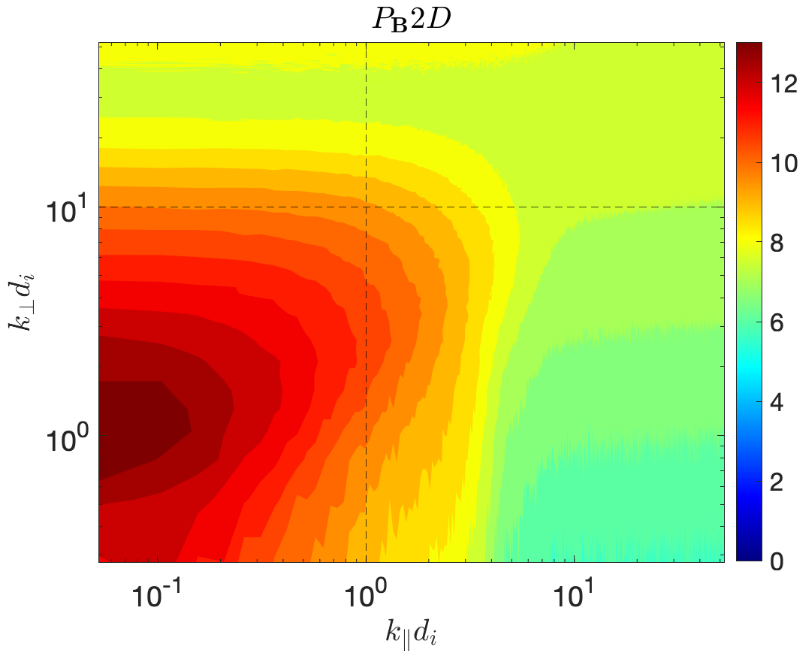


Figure 3: Reduce 2D PDF

Turbulent cascade

- Figure 1 shows the formation of current sheet structures. In panel (a) we identify current sheets and current filaments.
- Figure 3 shows the reduced 2D power spectral density of the magnetic fluctuation $P_{\mathbf{B}}2D(k_\perp, k_\|)$, where $k_\perp$ and $k_\|$ are the components of the wave vector perpendicular and parallel to $\mathbf{B}_0$.
- The system develops an anisotropic distribution of magnetic energy among several spatial scales consistent with the elongated shape of the structures in Figure 1.

Finding magnetic reconnection sites

3D magnetic reconnection is fundamentally different from 2D. Therefore, we propose a set of indicators to find reconnection sites in 3D.

Indicators:

C1) High Current-density structures;

C2) Non-zero parallel electric fields;

C3) Heated particles;

C4) Fast ions and electrons;

C5) Strong gradients in at least one component of the magnetic field and magnetic null regions.

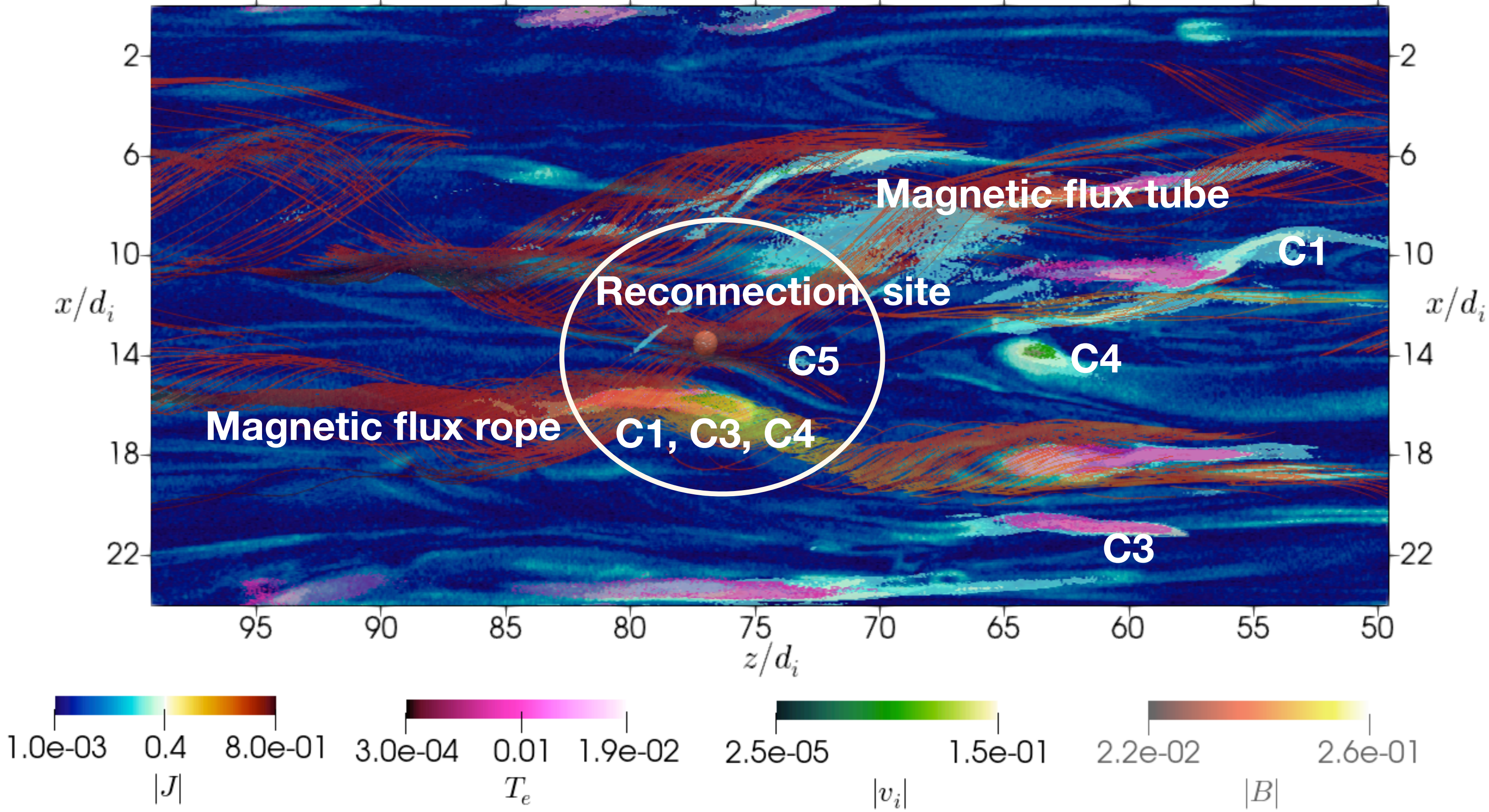
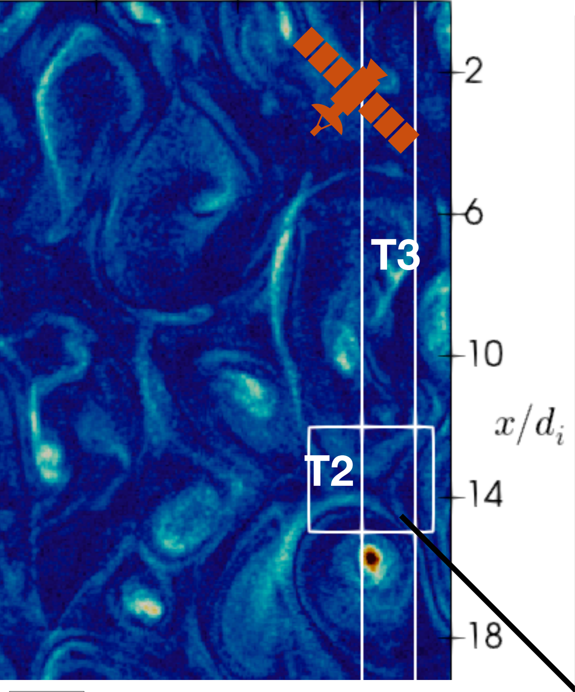


Figure 4: Magnetic reconnection indicators applied on our simulations

Results and discussion

- Figure 4 visualises our set of indicators. T_e is the electron temperature and v_i is the ion speed. Not all the high current density structures are colocated with fast and heated particles.
- The highly twisted magnetic flux rope breaks and reconnects with the surrounding magnetic tubes.
- Since the the electric field is highly sensitive to the particle noise due to the finite number of particles, the application of the indicator C2 in 3D PIC simulations is rather limited.



- Figure 5 shows the profiles of the ion velocity and magnetic field components measured by an artificial spacecraft passing through and near to the reconnection site. V_{A0} is the ion Alfvén speed. We observe the presence of slow-mode-polarised fluctuations, rotations in the magnetic field and changes in the sign of the correlation between magnetic field and ion velocity consistent with reconnection exhausts observed in the solar wind.

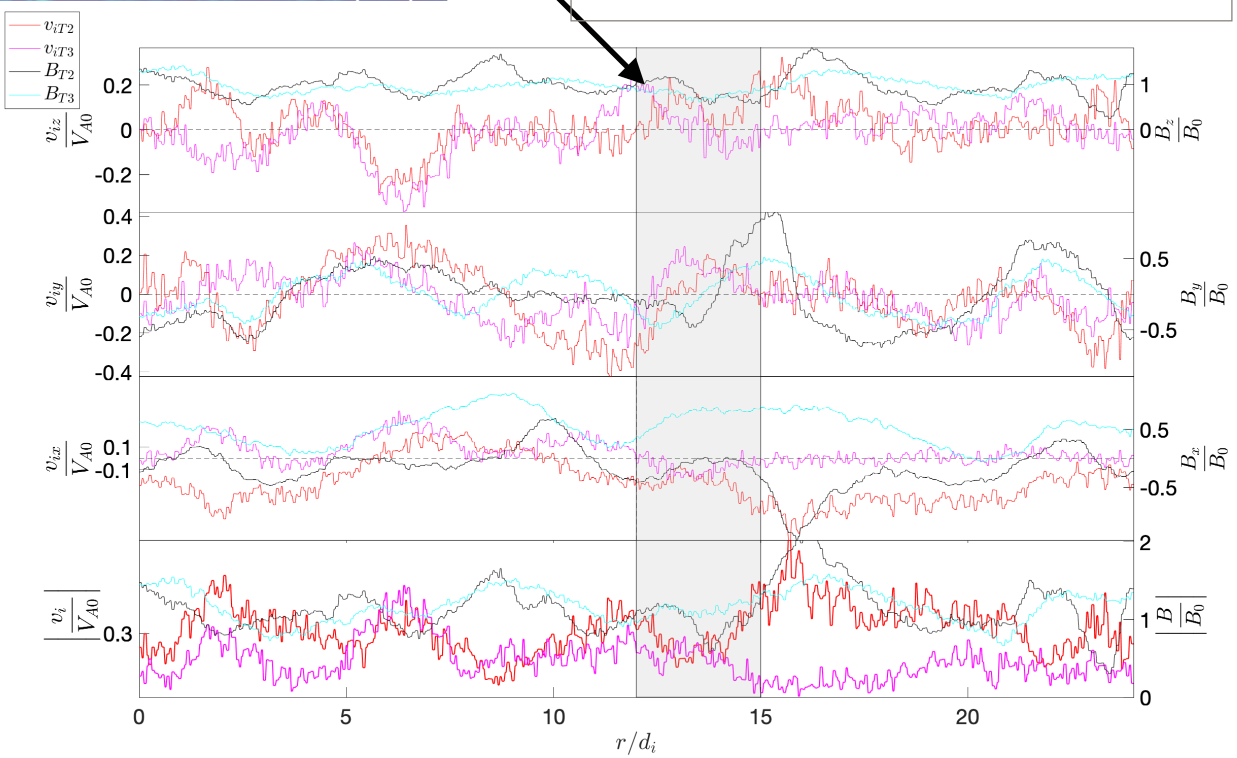


Figure 5: 1D trajectories passing through and near the reconnection region

Conclusions

- We establish a set of indicators for magnetic reconnection in 3D PIC simulations.
- We observe the spontaneous onset of 3D magnetic reconnection in a PIC simulation of decaying Alfvénic turbulence.
- The profiles of ion speed and magnetic field are consistent with reconnection events in the solar wind.
- Our results can be compared with measurements made by PSP and Solar Orbiter.

Acknowledgements

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