3D small-scale turbulent reconnection: energy transport and transfer.

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1. Numerical set up and Set of indicators

We use the PIC code *Plasma Simulation Code* (PSC, Germaschewski et al. 2016) to simulate anisotropic low-frequency counter-propagating Alfvén waves within an elongated box.

We define a **set of indicators to find reconnection sites** in our simulation based on intensity thresholds:

C1) Current-density structures.
C2) Fast ions and electrons.
C3) Heated particles.
C4) Energy transfer between fields and particles.
C5) Non-zero parallel electric fields.

- The exchange of magnetic connectivity (reconnection site) is surrounded by the regions that satisfy our criteria.
- The application of the indicator C5 in 3D PIC simulations is limited due to particle noise.

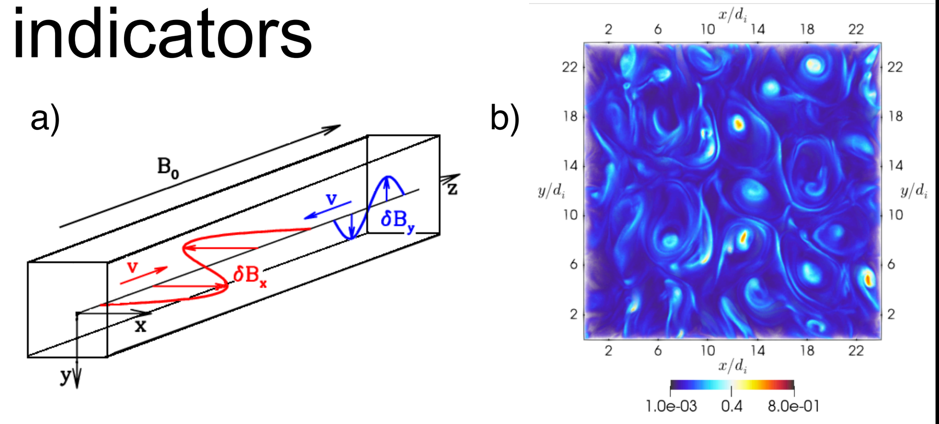


Fig 1. a) Simulation geometry; b) current structures in a 2D cut

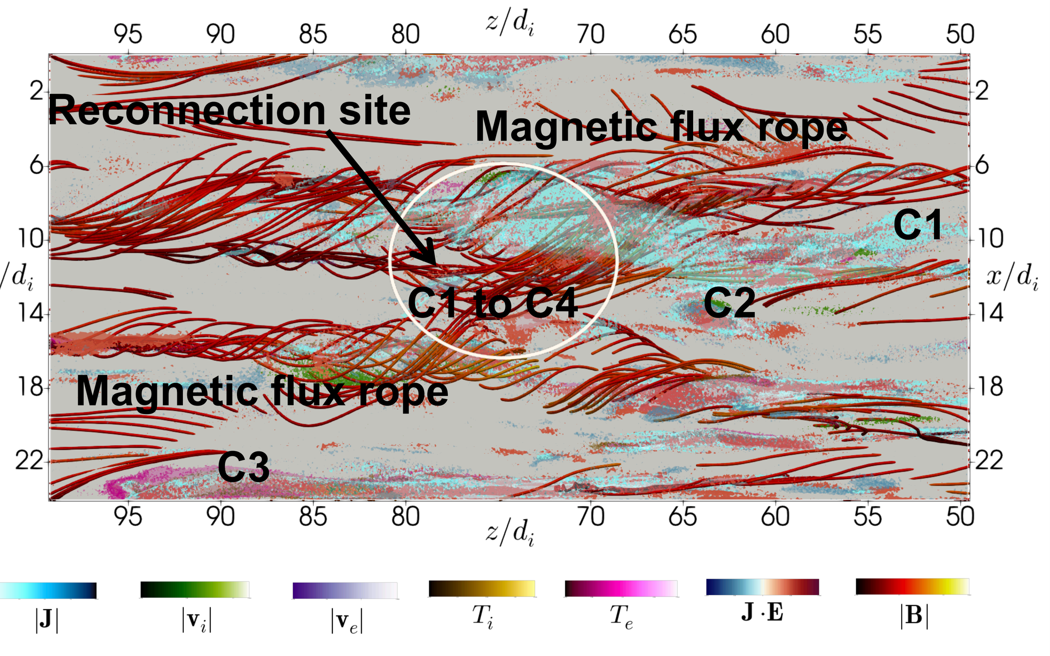


Fig 2. Reconnection indicators in context. For details see **Agudelo Rueda et al., JPP, 2021**.

2. Reconnection event

- Elongated flux ropes and current filaments.
- The event involves two reconnecting flux ropes.
- It is highly dynamic and asymmetric.
- Complex magnetic topology.

- We do a coordinate transformation to enhance the geometrical features in the plane perpendicular to the current structure that sustains the magnetic gradient.

- Multipolar out-of-plane- magnetic field.
- Strong out-of-plane electron motion.
- Electron streams along separatrices.
- Demagnetized ion motion.

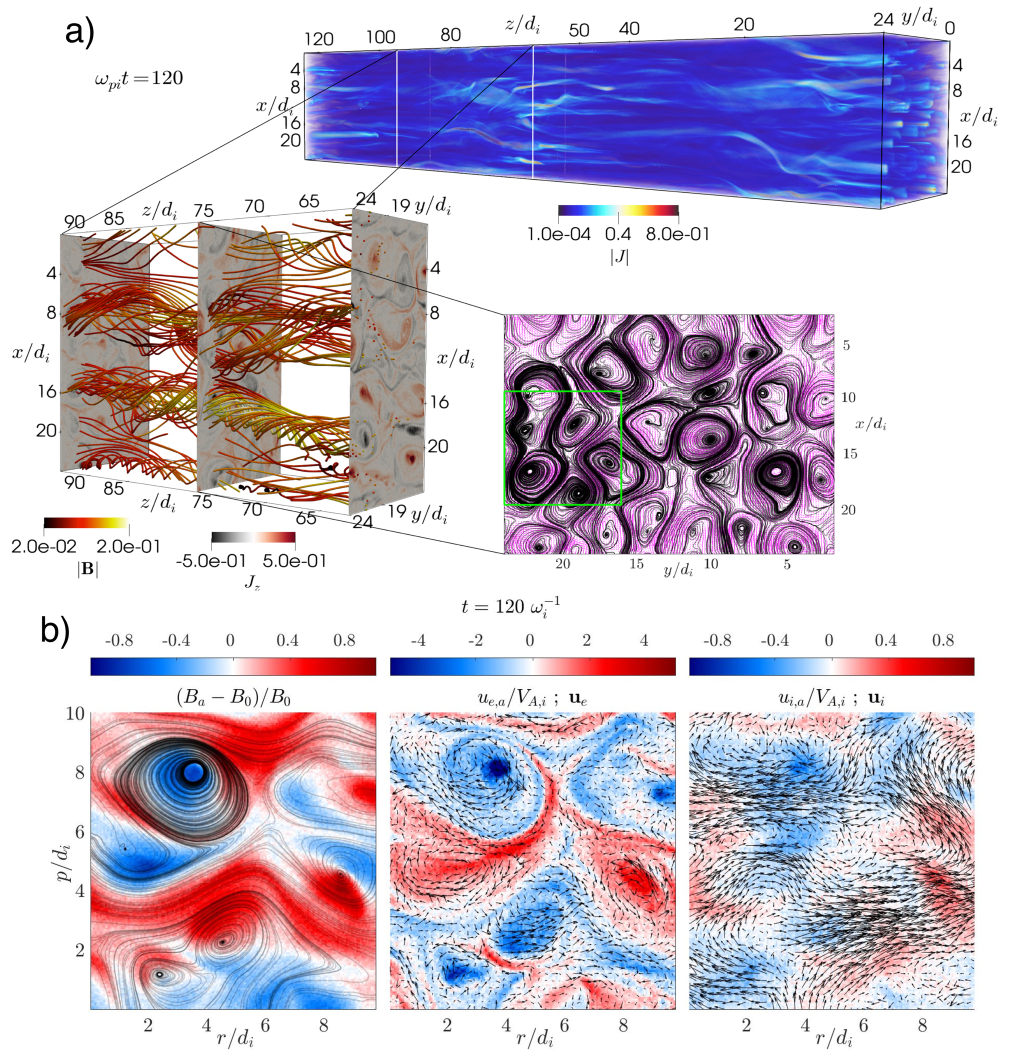


Fig 3. a) Extracting the region of interest; b) 2D cut of the out of the magnetic topology and particle motion

3. Energy distribution.

We use a two-fluid approach (Yin et al, 2001; Birn & Hesse, 2010) to study the spatial energy distribution associated with the reconnection event.

General "collisional" term

$$\frac{\partial f_s}{\partial t} + \mathbf{v_s}\cdot\nabla f_s + \frac{q_s}{m_s}(\mathbf{E}+\mathbf{v_s}\times\mathbf{B})\cdot\nabla_v f_s = \left(\frac{\partial f_s}{\partial t}\right)_c \quad (1)$$

$$\frac{d\varepsilon_s^k}{dt} + \mathbf{u_s}\cdot(\nabla\cdot\bar{\mathbf{P}}_s) + (\nabla\cdot\mathbf{u_s})\varepsilon_s^k - q_s n_{s\mathbf{u_s}}\cdot\mathbf{E} = m_s\mathbf{u_s}\cdot\Xi_s \quad (2)$$

- The electron diffusion region is dominated by the flow dilatation

$$\frac{d\varepsilon_s^{th}}{dt} + \nabla\cdot\mathbf{h_s} + \nabla\mathbf{u_s}:\bar{\mathbf{P}}_s + (\nabla\cdot\mathbf{u_s})\varepsilon_s^{th} = -m_s\mathbf{u_s}\cdot\Xi_s + \frac{1}{2}Tr\left(m_s\bar{\Xi}_s^2\right) \quad (3)$$

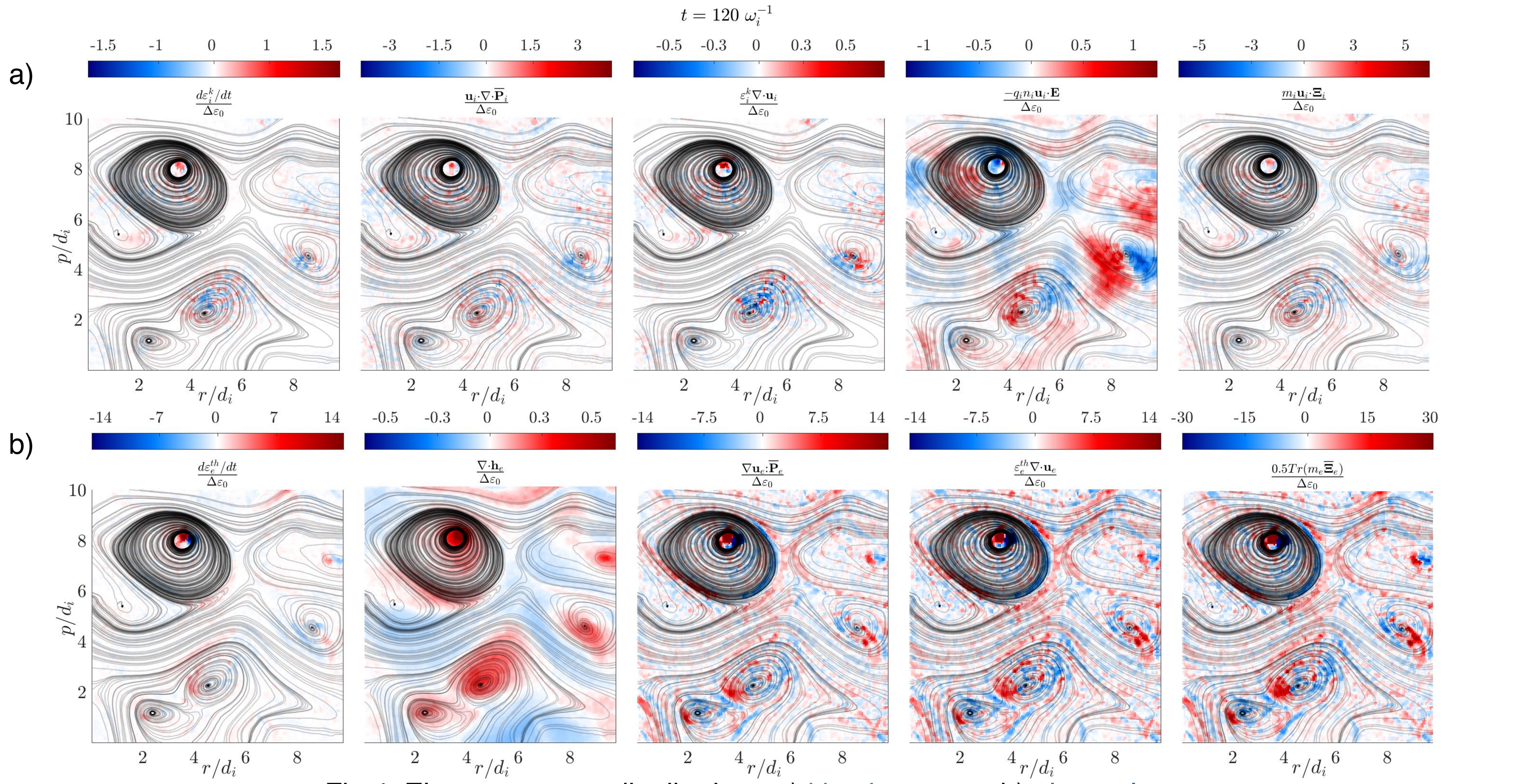


Fig 4. Electron energy distribution. a) kinetic energy; b) thermal energy.

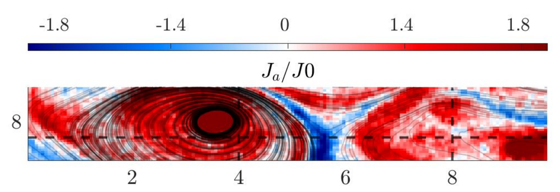
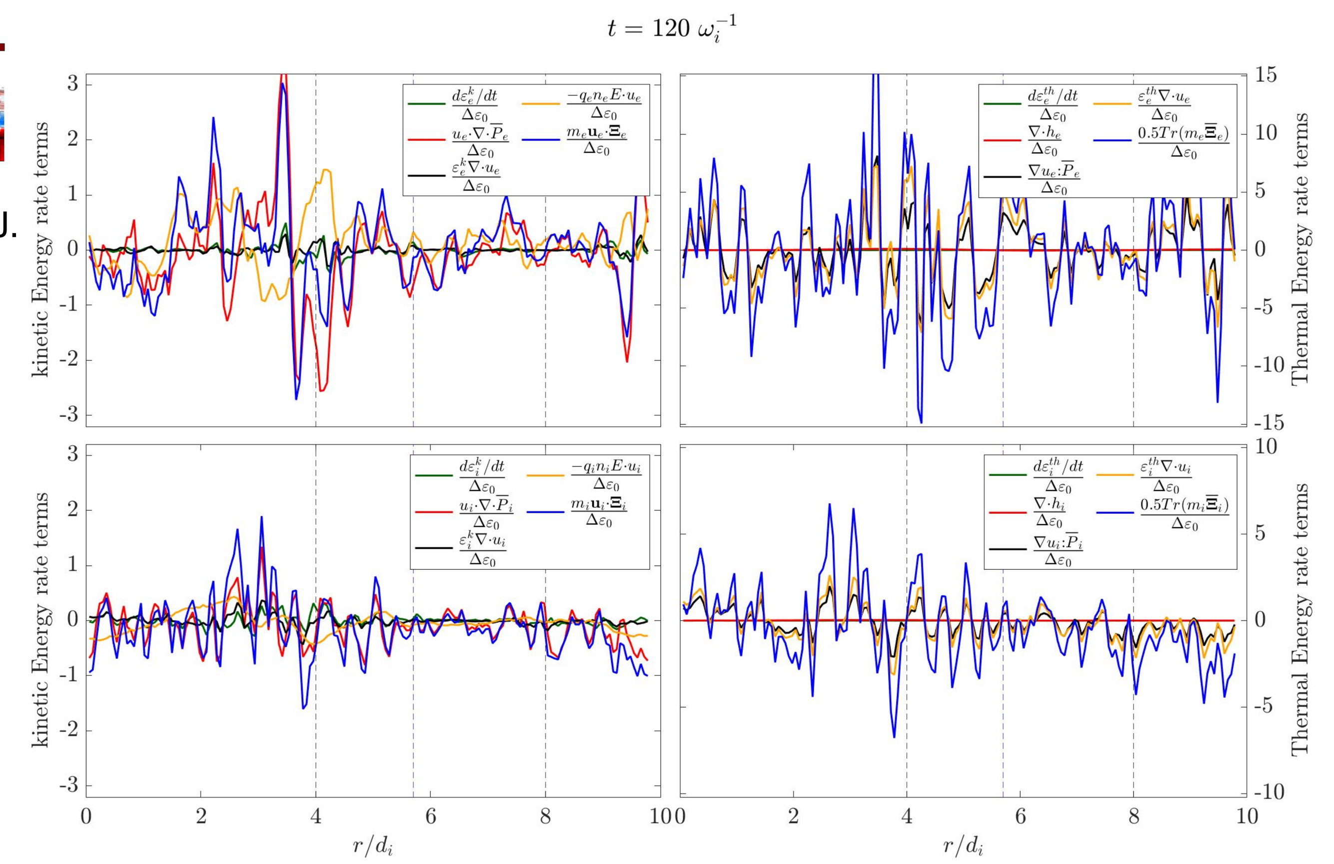


Fig 5. Out of the plane component of J.

Fig 6. 1D cuts of the energy density terms for electrons (top) and ions (bottom) along the horizontal dashed line of Fig 5.

- The electric field energy transfer (yellow) balances the flow of dilatation energy (red) at the center of the flux ropes.
- The thermal energy change is larger than the kinetic energy rate.
- The collisional contribution is not negligible.



Energy "dissipation"

- The energy dissipation surrogates peak at the core of the flux ropes.
- The isotropic expansion dominates the deviatory contribution
- The deviatory contribution is asymmetric in the electron diffusion region

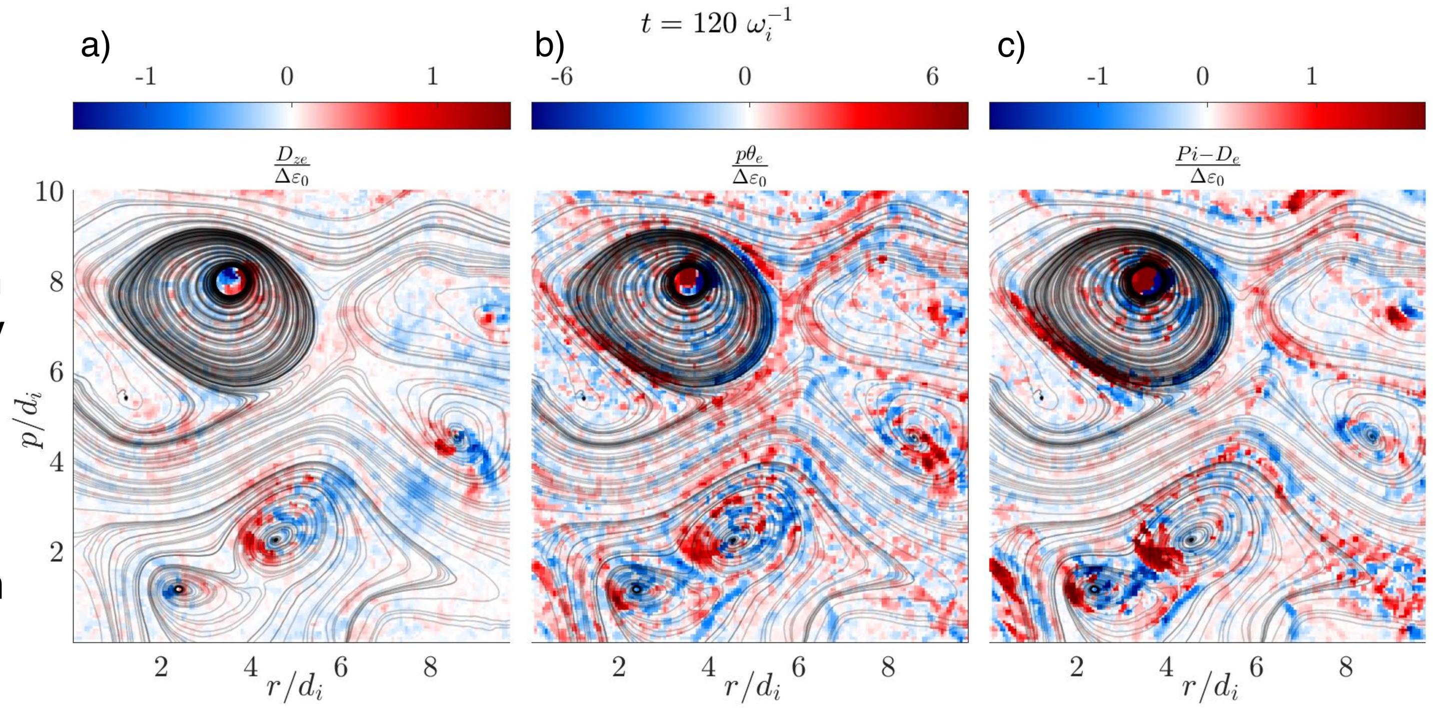


Fig 7. Dissipation surrogates: a) Energy transfer (Zenitani et al. 2011); b) Isotropic dilatation contribution and c) Deviatory contribution (Yang et al. 2017)

Summary and conclusions

- We set up anisotropic turbulence and observe the occurrence of magnetic reconnection.
- We propose a set of indicators to identify magnetic reconnection events in 3D PIC simulations.
- Within the reconnecting flux-ropes the energy is transformed through different channels.
- There is an important conversion of energy both within the flux ropes and in the reconnection region.
- The thermal energy terms present larger variations than the kinetic energy terms.
- Our findings suggest that the reconnection shape is dominated by the diagonal part of strain tensor.
- The effect of collisions appears to be non-negligible.
- We do not differentiate on the nature of these "collisional" contributions. Numerical heating, finite number of particles and correlation between density fluctuations and electromagnetic field fluctuations can account for these contributions.

Acknowledgments

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