Magnetic reconnection studies @ISC-Torino

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The Plasma Unit of the Institute of Complex Systems of the CNR at the Politecnico di Torino focuses on the theoretical and numerical analysis of magnetic reconnection processes in plasmas of interest for both space and fusion applications. In particular, we study the fundamental processes that govern the interaction between magnetic reconnection and fluid turbulence [1,2], the instability of plasmoids in a turbulent plasma [3], the control of magnetic islands [4] and reconnection instabilities driven by runaway electrons in a post-disruption plasma [5]. Here, we present the main results achieved so far and outline our ongoing activities.

Collisionless model for Magnetic Reconnection

$$\frac{\partial \nabla_\perp^2\varphi}{\partial t} = -[\varphi\,,\,\nabla_\perp^2\varphi] + \frac{2}{\beta_e}[\psi\,,\,\nabla_\perp^2\psi] + \frac{2}{\beta_e}\frac{\partial \nabla_\perp^2\psi}{\partial z}$$

$$\frac{\partial F}{\partial t} = -[\varphi\,,\,F] - 3[\psi\,,\,\nabla_\perp^2\varphi] + \frac{\partial \varphi}{\partial z} - 3\frac{\partial \nabla_\perp^2\varphi}{\partial z}$$

$$\boldsymbol{B} = \nabla\psi \times \hat{z} + \hat{z} \qquad F = \psi - \frac{(2\delta^2)}{\beta_e}\nabla_\perp^2\psi$$

$$\beta_e = 8\pi n_0 T_e / B_0^2 \qquad \delta = \sqrt{(m_e/m_i)}$$

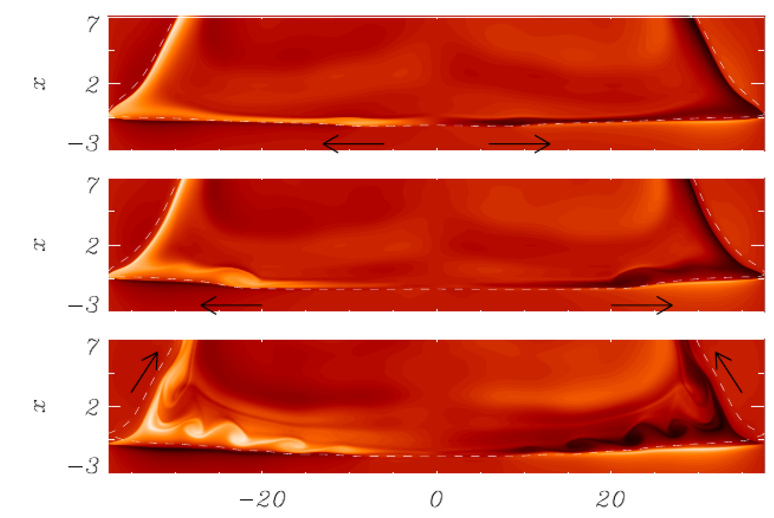
Perturbation

$$J_{pert} = J_0\sqrt{\frac{2}{\pi d_e^2}}\cos(k_y y + k_z z)\, e^{-\frac{(x-x_s)^2}{4d_e^2}} + 10^{-5} J_0 \Delta\Phi(y,z)$$

2D/Single helicity defined by a fixed ratio of k_z/k_y and $\Delta\Phi=0$

3D/Multiple helicty defined by multiple k_z and k_y and $\Delta\Phi\neq 0$

Problem relevant to astrophysical plasmas close to the magnetosphere (Burch, Science 2016)

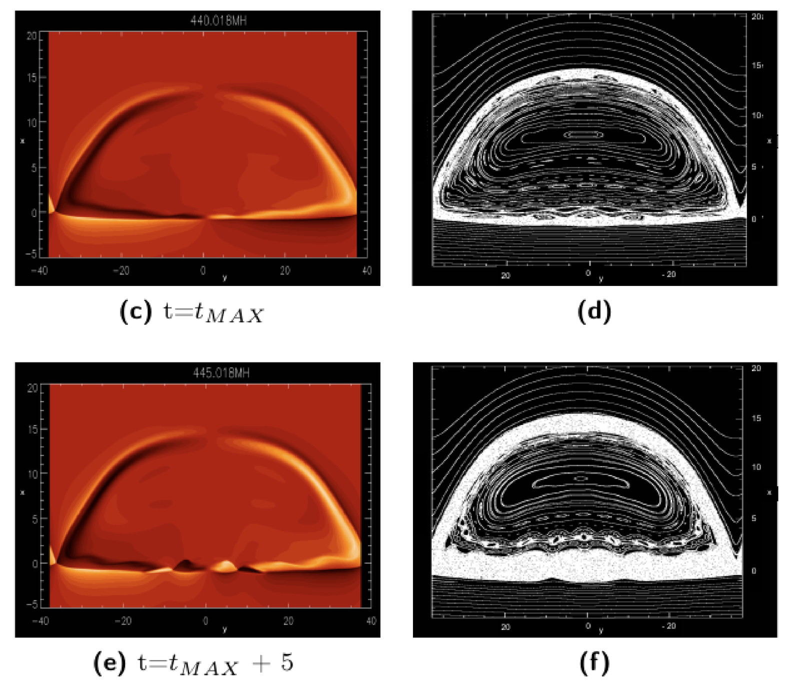


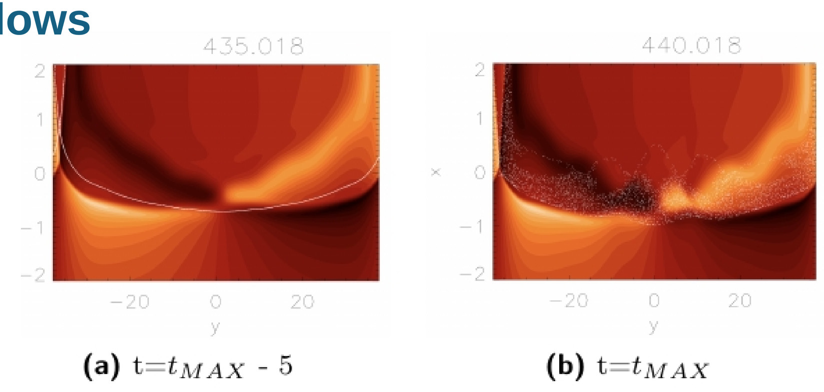
Grasso et al. PoP 27, 012302 (2020)

Developing of Kelvin-Helmholtz (fluid turbulence) on the edge of a 2D asymmetric magnetic island. Similar sttuctures have been observed also in gyrokinetic simulations of reconnection in fusion plasmas (Widmer, PoP 2025)

3D Results

KH and MR develop at the same time. Magnetic field line follow turbulent and magnetic flows





Marchetto et al. Submitted to PoP

Collisionless model for 2D turbulence

$$\frac{\partial \psi}{\partial t} + [\varphi,\,\psi] = -d_e^2\frac{\partial J}{\partial t} - d_e^2[\varphi,\,J] - \eta(J - J_{eq})$$

$$\frac{\partial U}{\partial t} + [\varphi,\,U] = [J,\,\psi] + \nu\nabla^2 U \qquad \boldsymbol{v} = \boldsymbol{e}_z \times \nabla\varphi$$

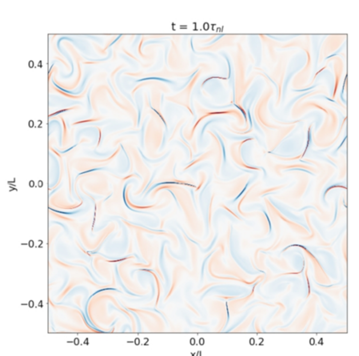
$$J = -\nabla^2\psi \quad U = \nabla^2\varphi \qquad \boldsymbol{B} = B_0\boldsymbol{e}_z + \nabla\psi \times \boldsymbol{e}_z$$

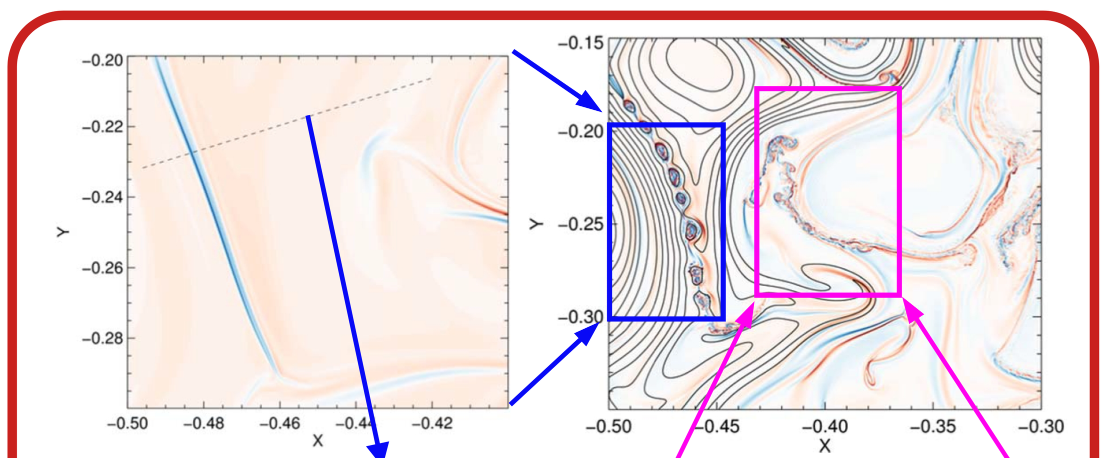
Perturbation for a freely decading turbulence

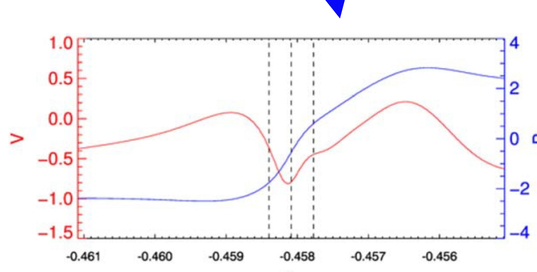
$$\psi = -\sum \psi_{0mn}\sin(k_m x + \xi_{1mn})\sin(k_n y + \xi_{2mn})$$

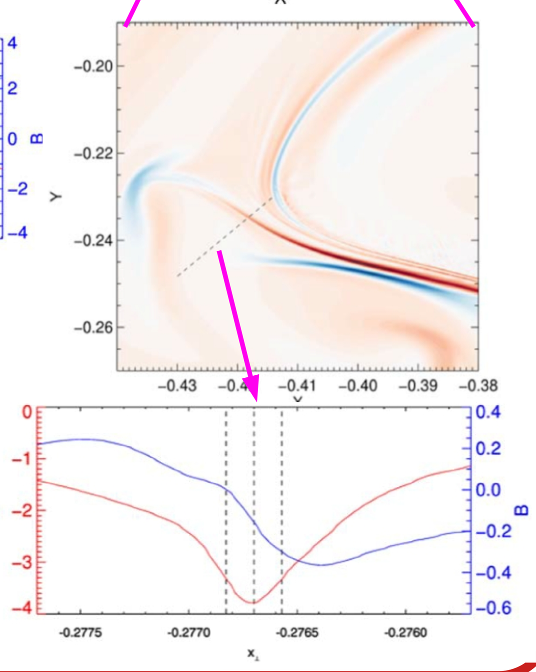
$$\varphi = \sum \varphi_{0mn}\sin(k_m x + \xi_{3mn})\sin(k_n y + \xi_{4mn})$$

The early dynamics leads to the formation of thin and elongated current and vorticity sheets. They evolve according to plasmoid or KH instability.





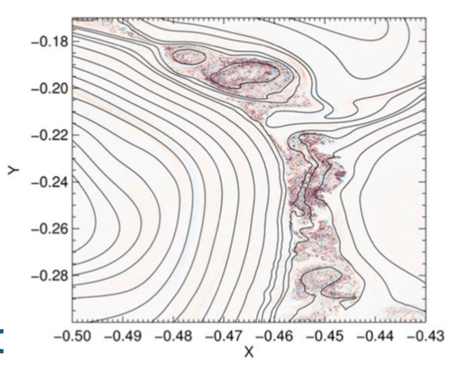


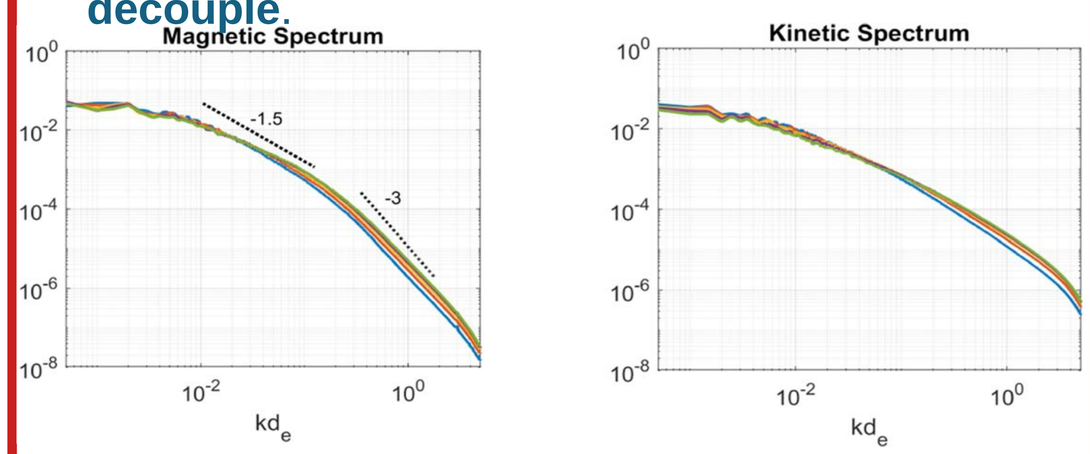


Plasmoid or KH instability dominates depending on the relative shear magnitude across the layer.

Borgogno et al. APJ, 929:62 (2022)

Plasmoids are accompanied by the generation of small scale current and vorticity structures leading to large turbulent regions where coherent magnetic structures disappear. As a consequence magnetic and kinetic spectrum decouple.





On going work: exploring the role of ion sound Larmos radius on this turbulent cascade

Model for runaway current driven magnetic reconnection

$$\frac{\partial \psi}{\partial t} + [\varphi,\psi] + \eta(J - J_{RE}) + \frac{\partial\varphi}{\partial z} + \rho_s^2\frac{\partial U}{\partial z} = 0$$

$$\frac{\partial U}{\partial t} + [\varphi, U] - [J,\psi] - \frac{\partial J}{\partial z} = 0 \qquad J = -\nabla^2{}_\perp\psi, \quad U = \nabla^2{}_\perp\varphi$$

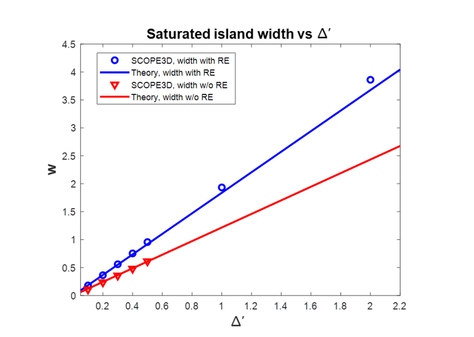
$$\frac{\partial J_{RE}}{\partial t} + [\varphi, J_{RE}] + \frac{c}{v_A}\left([\psi, J_{RE}] - \frac{\partial J_{RE}}{\partial z}\right) = 0$$

Helander et al. PoP (2007)

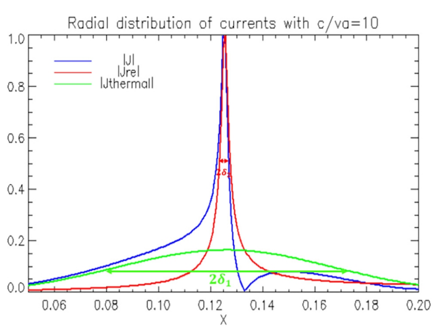
SH Linear results

$$\frac{\gamma^{5/4}}{\eta^{3/4}k_y^{1/2}}\frac{2\pi\Gamma(3/4)}{\Gamma(1/4)} = \Delta' - i\pi\frac{k_y J'_{RE0}}{|k_y|}$$

Weak influence of the runaway electron current on the linear growth rate which follows the FKR growth Poloidal rotation frequency of the magnetic island proportional to the REs profile



REs lead to a 50% increase in the magnetic island width at saturation



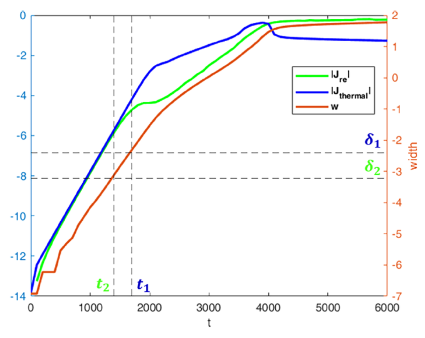
The conservation of the RE current leads to strongly peaked current profiles

$$\delta_1 = \gamma^{1/4}\eta^{1/4}k_y^{-1/2} \quad \textbf{Resistive layer}$$

$$\delta_2 = \frac{\gamma v_A}{k_y c} \quad \textbf{Inner layer}$$

RE current density peaks on the radial scale δ_1, while the thermal electron current is concentrated on δ_2

SH Nonlinear results

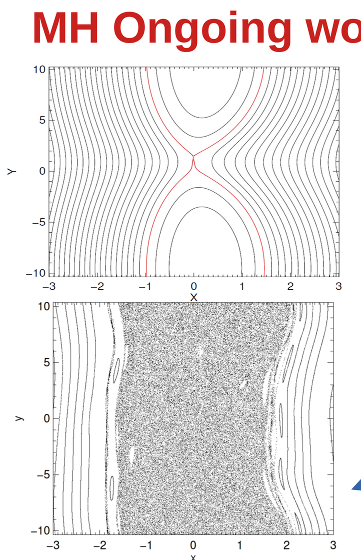


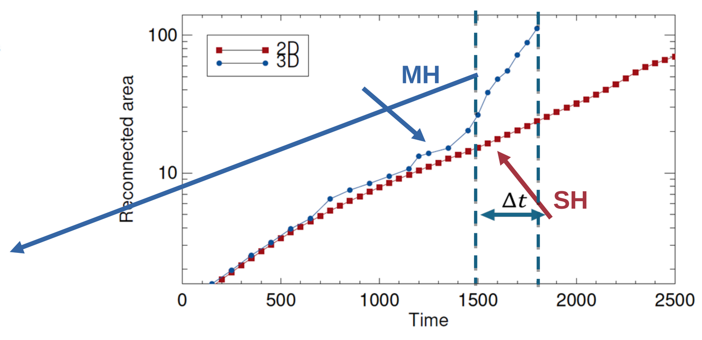
RE become nonlinear when the magnetic island width w is comparable with δ_2, while thermal electrons when w~δ_1

Singh et al. PoP 30, 12114 (2023)

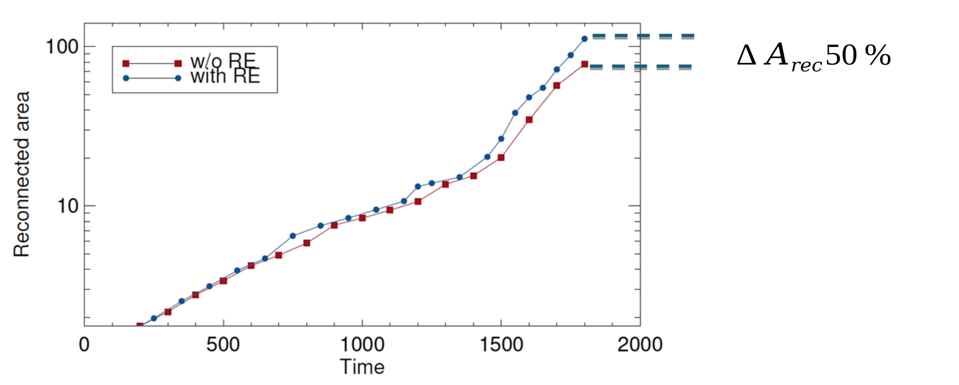
MH Ongoing work

Magnetic choas has been observed to have beneficial effect on the REs termination in Bandaru et al, PPCF 63 (2021). **Understanding the interaction of Res and magentic cahos is crucial**





Transition from local to global stochasticity in Δt~300τ A (), in agreement with Bandaru



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