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# Magnetic reconnection in the presence of magnetic chaos: effects on secondary instability via 3D simulation

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**Overview**

This study investigates how magnetic chaos, and the emergence of multiple helicities affect the development of Kelvin-Helmholtz (KH) instabilities in magnetic reconnection events. While previous analyses have focused on single helicity (SH) modes in two-dimensional (2D) settings [1], we extend the study to a three-dimensional (3D) framework, where multiple helicities (MH) can develop and magnetic field lines can become stochastic. In this context, secondary KH instabilities appear earlier and with altered morphology, influencing the energy dynamics and spatial structure of the plasma.

Magnetic reconnection [2] is a key process for the rapid conversion of magnetic energy into plasma kinetic energy and flows, often accompanied by secondary instabilities. These instabilities, such as KH-type vortex layers, can develop along separatrices or internal jets when velocity shears are present [3,1]. Although reconnection is often studied in 2D for simplicity and the presence of a strong *guide* field, realistic configurations, including those in astrophysical and fusion contexts, require a full 3D treatment. This allows for the growth of multiple helicities, the loss of nested flux surfaces, and the emergence of chaotic field-line behaviour.

**Model and Numerical Framework**

The system is modelled using a reduced magnetohydrodynamic framework for a collisionless plasma, accounting for variation perpendicular and parallel to the guide field, which includes electron inertia but neglects finite temperature effects [4]. The equilibrium configuration consists of a sheared magnetic field with an asymmetric current profile. Perturbations are introduced via a dominant single helicity (1,1) mode combined with a small random noise, enabling the spontaneous growth of additional helicities such as (2,1), (3,1), and (3,2). The simulations are performed using the SCOPE3D code, which resolves the full 3D structure on a high-resolution grid.

**Key Results**

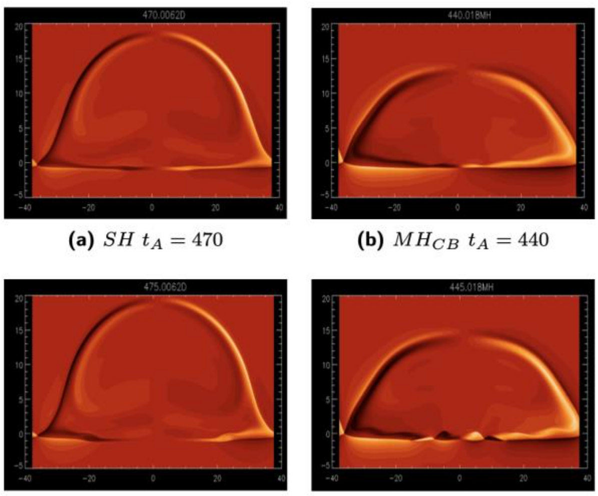
1. Growth of Multiple Helicity Modes: Secondary helicities start growing early in the simulation due to initial noise. Their interaction becomes nonlinear and modifies the evolution of the main mode.
2. Early Onset of KH Instability: The KH instability develops sooner in the multi-helicity case compared to the SH case. It originates along peak vorticity lines rather than the separatrix and exhibits asymmetric and ripple-like structures.
3. Magnetic Chaos: The magnetic field lines become chaotic, starting at the separatrix and progressively filling the island. The onset of chaos correlates with the growth of secondary helicities and evolves differently when the system is perturbed with different additional helicities, as they resonate in different places (Fig.1).
4. Energy Redistribution: In the presence of multiple helicities, magnetic energy is more efficiently converted into kinetic energy. This is reflected in faster growth of kinetic energy components during the nonlinear phase.
5. Structural Differences: In 3D, electrostatic potential and vorticity fields are no longer constrained to follow the magnetic island separatrix. This leads to more complex and asymmetric structures, absent in the 2D treatment.

**Integrated Behaviour and Diagnostics**

The reconnection process is quantified by monitoring the area of reconnected regions and the evolution of energy terms. Despite differences in dynamics, the total reconnected area remains similar between SH and MH configurations. However, the MH case shows earlier energy redistribution, indicating a faster nonlinear transition. The presence of different helicities also affects the structure of Poincaré sections, indicating modifications in field-line topology and coherence.

**References**

[1] Grasso D. et al., Phys. Plasmas 27 (2020)
[2] Biskamp D., Magnetic Reconnection in Plasmas (Cambridge University Press, 2000)
[3] Del Sarto D. et al., Plasma Phys. Controll. Fusion 53 (2011).
[4] Tassi E. et al., J. Plasma Phys. 27 (2020)



**(a)** $SH\ t_A = 470$ **(b)** $MH_{CB}\ t_A = 440$

**(c)** $SH\ t_A = 475$ **(d)** $MH_{CB}\ t_A = 445$

Fig.1: Contour plot of vorticity in the *x,y* plane at the birth of secondary instability: SH (left) and MH (right)