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Reconnection and particle acceleration due to tilt-kink instabilities

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Abstract

Magnetic reconnection is apparent in many astrophysical environments, on very different energy and length scales. It is suggested as one of the potential mechanisms behind particle acceleration up to highly nonthermal energies in the solar corona or in more exotic environments like relativistic flows around black holes and neutron stars. We present a numerical study where we use a combination of resistive magnetohydrodynamics (MHD) and test-particle methods to analyze particle acceleration up to relativistic speeds in two repelling, unstable, current channels. The tilt-kink instabilities occurring are proposed as a novel reconnection initiation mechanism. The effects on particle acceleration in the violent, reconnection-dominated evolution are discussed.

MHD equilibrium and stability

Two flux ropes are modeled by prescribing an ideal MHD equilibrium in Cartesian coordinates on a square region in the (x, y)-plane, with two anti-parallel current channels, initially in the z-direction (see Figure 1).

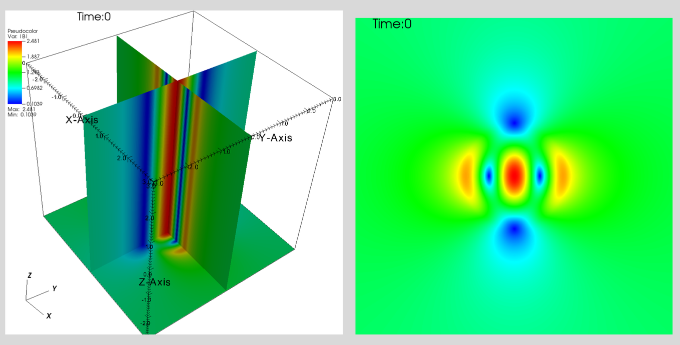


Figure 1: Equilibrium magnetic field magnitude of two repelling flux ropes in 3D (left) and in the (x, y)-plane, for , $B_z(t = 0) = 0.1$ (in dimensionless units).

An ideal MHD equilibrium can be established in two ways [1]:

- *In a force free equilibrium (uniform plasma pressure), with a spatially varying, vertical force-free magnetic field $B_z(x, y)$ balancing the Lorentz force.*
- *By a pressure gradient balancing the Lorentz force $\nabla p = \mathbf{J} \times \mathbf{B}$.*

2D stability:

- *A linear stability analysis for 2D incompressible MHD, based on an energy principle, has been carried out [1], showing that a perturbed ideal MHD equilibrium is sensitive to a tilt instability in the (x, y)-plane.*
- *This leads to the creation of (near) singular current sheets in which particles can accelerate efficiently.*

It is shown by [2] that additional effects come into play in a 3D setup:

- *The current channels may be unstable to an ideal kink instability, depending on typical magnetic field strengths and system size, due to field line bending with respect to the vertical direction.*
- *If the z-component of the magnetic field is strong enough, the magnetic tension may also stabilize or delay kink deformations and even prevent tilt development.*

Reconnection and particle dynamics

- *The tilt instability is an ideal MHD instability, from which it can be concluded that the resistivity has little effect on the (linear) onset phase of the instability [1]. Once the instability develops and the physics becomes naturally nonlinear, it allows for fast reconnection of the field lines.*
- *Excess magnetic field energy due to reconnection of field lines can efficiently accelerate charged particles in the plasma up to non-thermal, relativistic velocities.*
- *To resolve particle dynamics in phase space we apply a relativistic guiding center approximation to first order. Test particle dynamics are considered in slowly varying fields, governed by the equations of motion for the guiding center [3]:*

$$\frac{d\mathbf{R}}{dt} = \frac{\left(\gamma v_\parallel\right)}{\gamma}\hat{\mathbf{b}} + \frac{\hat{\mathbf{b}}}{B\left(1-\frac{E_\perp^2}{B^2}\right)} \times \left\{ -\left(1-\frac{E_\perp^2}{B^2}\right) c\mathbf{E} + \frac{\mu_r c}{\gamma q}\nabla\left[B\left(1-\frac{E_\perp^2}{B^2}\right)^{1/2}\right] \right.$$
$$\left. + \frac{c m_0 \gamma}{q}\left(v_\parallel^2\left(\hat{\mathbf{b}}\cdot\nabla\right)\hat{\mathbf{b}} + v_\parallel\left(\mathbf{u_E}\cdot\nabla\right)\hat{\mathbf{b}} + v_\parallel\left(\hat{\mathbf{b}}\cdot\nabla\right)\mathbf{u_E} + \left(\mathbf{u_E}\cdot\nabla\right)\mathbf{u_E}\right) + \frac{v_\parallel E_\parallel}{c}\mathbf{u_E}\right\},$$

$$\frac{d\left(m_0\gamma v_\parallel\right)}{dt} = m_0\gamma\mathbf{u_E}\cdot\left(v_\parallel^2\left(\hat{\mathbf{b}}\cdot\nabla\right)\hat{\mathbf{b}} + v_\parallel\left(\mathbf{u_E}\cdot\nabla\right)\hat{\mathbf{b}}\right)$$
$$+ qE_\parallel - \frac{\mu_r}{\gamma}\hat{\mathbf{b}}\cdot\nabla\left[B\left(1-\frac{E_\perp^2}{B^2}\right)^{1/2}\right],$$

$$\frac{d\left(m_0\gamma^{*2}v_\perp^{*2}/2B^*\right)}{dt} = \frac{d\mu_r}{dt} = 0$$

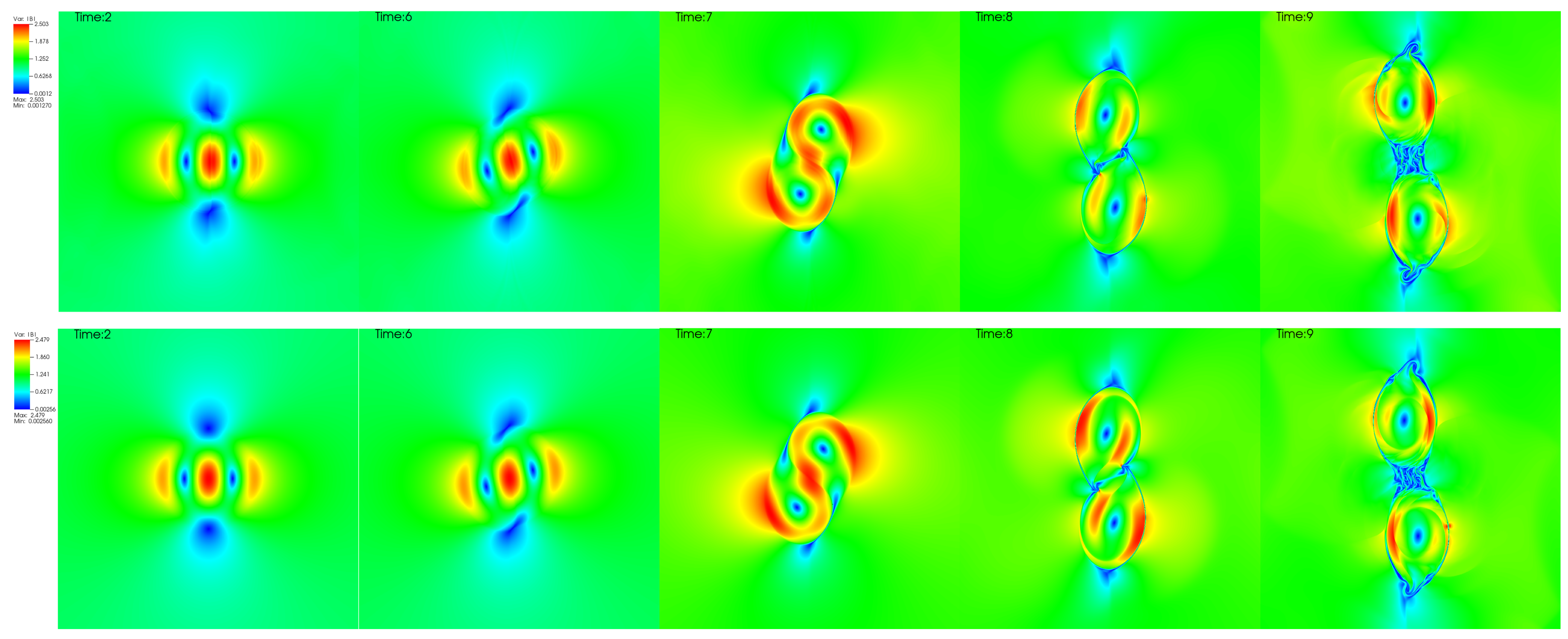
- *Relativistic effects modify classical drifts, because $m \to m_0\gamma$, and constant magnetic moment $\mu \to \mu_r$*
- *There is a purely relativistic, drift in the direction of $\mathbf{E}_\perp$, of the order of v^2/c^2*
- *For typical solar corona conditions (see Table 1), the guiding center approximation is accurate because the gyroradius $R_c \ll$ cell size $\left(\mathcal{O}\left(10^6 m\right)\right)$ [4].*

Table 1: Typical values for plasma parameters in the solar corona

particle	$B\,[T]$	$T\,[K]$	$n\,[\frac{1}{m^3}]$	$v_{th}\,[m/s]$	$\beta\,[-]$	$R_c\,[m]$	$\gamma\,[-]$
electron	0.03	10^6	10^{16}	$5.5 \cdot 10^7$	$4 \cdot 10^{-4}$	10^{-3}	1.0002
proton	0.03	10^6	10^{16}	$1.3 \cdot 10^6$	$4 \cdot 10^{-4}$	$4.4 \cdot 10^{-2}$	1.0000

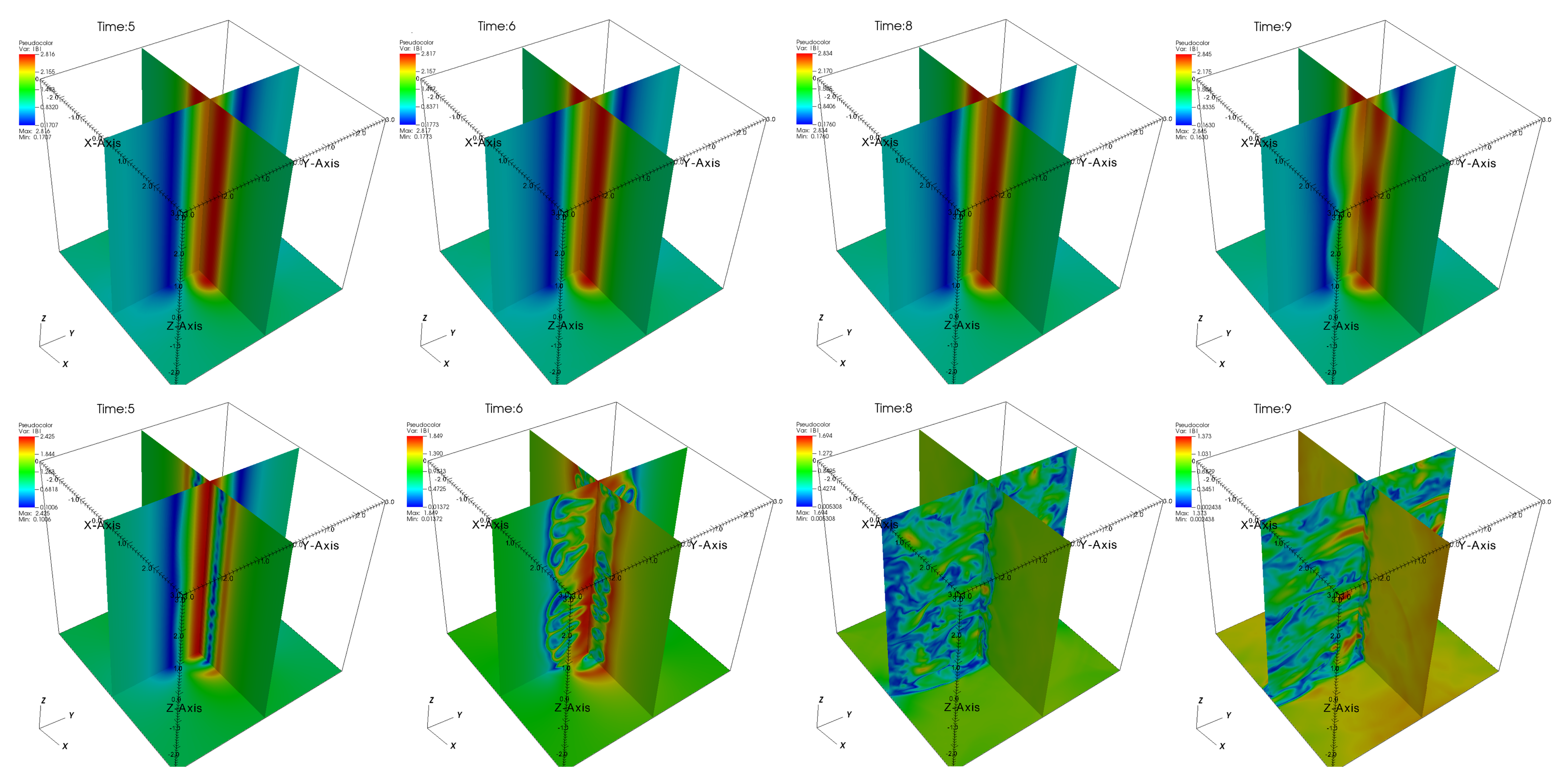
Numerical results in 2.5D and 3D

- *Simulations are done with the block adaptive MPI-AMRVAC code [5].*
- *The resistive, compressible MHD equations are solved in 2.5D (Figure 2) and 3D (Figure 3), in combination with the guiding center equations at every timestep.*
- *100.000 test particles (electrons and protons) are initialized at random positions, with a thermal velocity (see panel 1 of Figure 4).*



$t = 2$ $t = 6$ $t = 7$ $t = 8$ $t = 9$

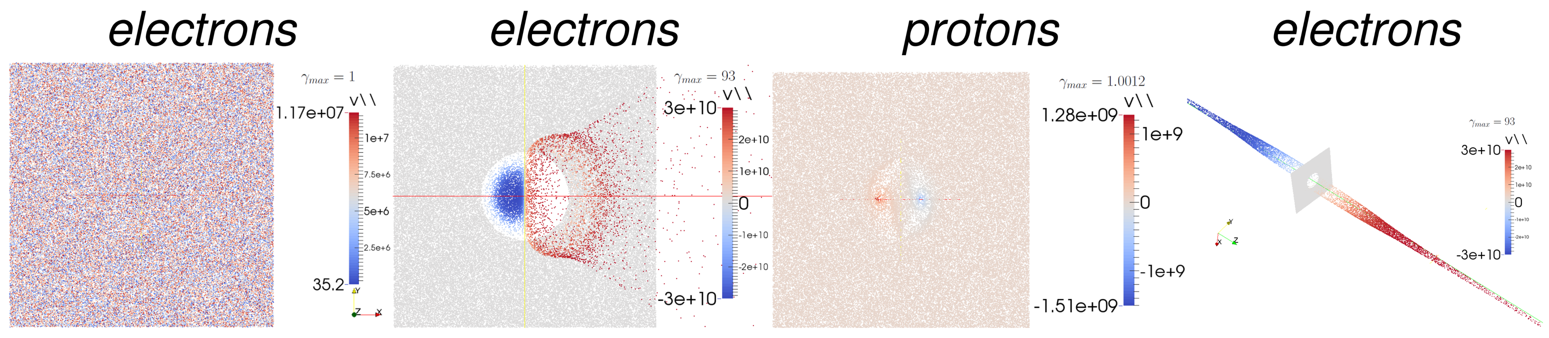
Figure 2: MHD evolution of the magnetic field magnitude in the (x, y)-plane of a force free equilibrium in 2.5D (top five figures) and a pressure gradient equilibrium (bottom five figures), with initial vertical magnetic field $B_z = 0.1$.



$t = 5$ $t = 6$ $t = 8$ $t = 9$

Figure 3: 3D MHD evolution of the magnetic field magnitude of a force free equilibrium (top four figures) and a pressure gradient equilibrium (bottom four figures), both with initial vertical magnetic field $B_z = 0.1$.

electrons *electrons* *protons* *electrons*



$t = 0$ *(x, y)-plane* $t = 8$, *(x, y)-plane* $t = 8$, *(x, y)-plane* $t = 8$, *3D view*

Figure 4: Particle positions in a 2.5D pressure gradient equilibrium evolution, colored by parallel velocity (in cgs units).

Conclusions

- *In 2.5D the tilt instability develops faster for a force free equilibrium, but both equilibra show a similar evolution from $t = 6$ onwards.*
- *in 2.5D there is a clear exponential growth of the peak current in the reconnection regions, which indicates efficient particle acceleration.*
- *Secondary islands (reconnection) are only visible in 2.5D due to high resolution.*
- *in 3D simulations, the force free equilibrium yields a much slower evolution, possibly due to stabilization via the kink in the vertical direction. The kink enhances the instability in the pressure gradient equilibrium for $B_z(t = 0) = 0.1$*
- *Electrons accelerate much faster and nearly reach the speed of light in and near the current channels compared to protons.*

References

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