Explosive nonlinear growth of double tearing mode: plasmoid formation and test particle acceleration

T. AKRAMOV[1], H. BATY[1]

[1] *Observatoire Astronomique de Strasbourg, Université de Strasbourg, CNRS, UMR 7550, 11 rue de l'université, F-67000 Strasbourg, France*

Magnetic reconnection is a fundamental process in astrophysical and laboratory plasmas, where a change of magnetic field topology allows the conversion of magnetic energy into kinetic and thermal energies. In particular, double current sheet configurations are known to lead to a fast and explosive reconnection phase during the non linear evolution of double tearing modes (DTM) once a critical threshold in the primary islands structure is reached [1]. The latter phase weakly depends on the resistivity η with a characteristic time scaling as $\eta^{0.05-0.2}$ [2, 3], contrary to the early (linear and Rutherford) resistive phases where the growth-times scale as $\eta^{1/2}$ and η^{1} respectively.

In this work, we investigate in detail the explosive growth phase via two-dimensional (2D) magnetohydrodynamic numerical simulations, considering in particular low η values for which small secondary plasmoids can form [4]. Finally, the acceleration of test particles is examined in such reconnecting systems, in order to discuss a possible application for the production of energetic particles in solar flares.

Model setup

We consider an usual set of 2D compressible and resistive MHD equations in (x,y) cartesian geometry [3]. A double Harris current sheet configuration is assumed, with an equilibrium magnetic field parallel to the y-axis and varying with x

$$B_x = 0, B_y = B_0[1 - \tanh(\frac{x+x_0}{a}) + \tanh(\frac{x-x_0}{a})], \tag{1}$$

where a is the half-width of each current sheet and $\pm x_0$ are the locations of the two current sheets. An isothermal plasma with a small plasma-β parameter is also considered, as $\beta = 0.2$. We set the ratio of specific heats γ equal to $5/3$ and choose units such that the magnetic permeability is unity. We also set $B_0 = 1$ and $a = 0.2$ to define our normalization.

The MHD simulations are carried out in a spatial domain $-L_x/2 \leq x \leq L_x/2$ and $-L_y/2 \leq y \leq L_y/2$, where $L_x = L_y = 4$. Fixed boundary conditions are applied at the two boundaries in the x-direction, and periodic boundary conditions are used in the y-direction. A value $x_0 = 0.5$ is chosen in order to have initially unstable DTM modes of wavenumber k (as $ka \lesssim 1$ with

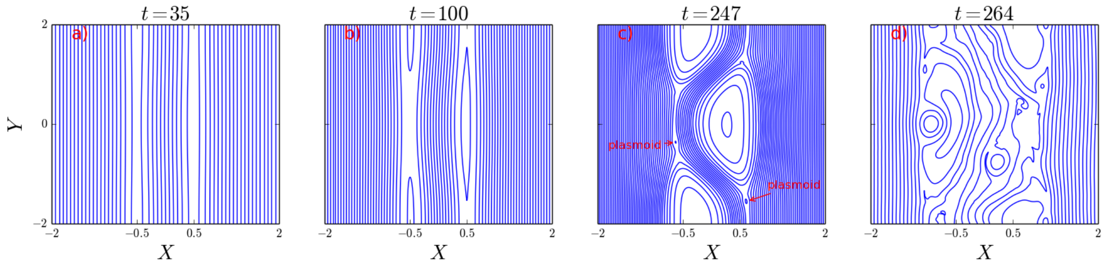

Figure 1: *Magnetic field lines corresponding to different phases of the DTM development (see Fig. 2). The explosive phase is plotted in panel (c) at a given time where plasmoids are visible.*

$k = 2\pi/L_y$ is required by linear stability theory), and non linear explosive growth (as $kx_0 \lesssim 1$ is necessary, see [1]). We use the general finite-volume based MPI-AMRVAC code [5], with 960×960 uniformly distributed grid points.

Finally, charged particles are introduced in a second code at different times of the MHD simulations in order to test potential acceleration of electrons and ions during different phases of DTM. For simplicity a single particle of effective mass $m = 10m_e$ is considered (m_e being the electron mass). A standard second-order (Boris-Buneman) time integrator is used to solve non relativistic Lorentz equations. The integration time is $t_{int} = 4.4 \times 10^3 \tau_g$ (leading to $t_{int} \simeq \tau_A$), where τ_g is the gyro-period and $\tau_A = 2x_0/V_a$ is the Alfvén time. The energy spectra are obtained with 10^4 initial mono-energetic ($|\mathbf{v}_0| = 10^{-3}V_A$) particles, initiated with random coordinates $x \in [-1 : 1]$, and $y \in [-2 : 2]$, and random directions. The electromagnetic structure is assumed to be invariant for the time integration in the third z-direction.

Numerical results

- Typical DTM development is explosive

A small divergence free perturbation is added to the previous MHD equilibrium in order to start the simulations. The typical time evolution of the DTM is plotted in Figs 1-2 for a case $\eta = 5 \times 10^{-5}$. Indeed, using the maximum velocity component $|\mathbf{v}_y|$ as a diagnostic measure of the instability magnitude, one can clearly see the four different phases in Fig. 2 with the corresponding magnetic field lines plotted in Fig. 1. A linear phase (a) is followed by a non-linear saturation (b, Rutherford regime), the fast/explosive reconnection (c), and a relaxation towards a final state (d). The fast reconnection is characterized by the coalescence of the two primary islands, and is enriched by the formation of plasmoids for this resistivity value (as the local Lundquist number based on the dynamic current sheet length exceeds the critical value of 10^4). The explosive character observed for $200\tau_A \lesssim t \lesssim 250\tau_A$ is confirmed as we obtained $|\mathbf{v}_y| \sim exp(\sigma(t)t)$, where $\sigma(t)$ is a measured instantaneous growth rate.

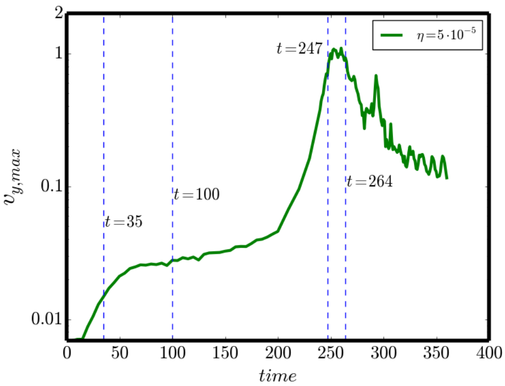

Figure 2: *Maximum value of* $|v_y|$ *as a function of time for a simulation using* $\eta = 5 \times 10^{-5}$. *The times corresponding to panels of Fig. 1 are indicated with vertical lines.*

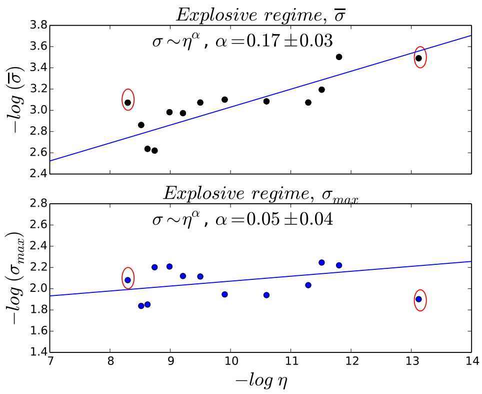

Figure 3: *Average (top panel) and maximum (bottom panel) measured growth rates of the explosive phase, as a function of the resistivity value. The two extreme points (with circles) are excluded for the linear fit.*

- *Resistivity dependence for the explosive phase*

Using different resistivity values in the range [$2 \times 10^{-6} : 2.5 \times 10^{-4}$], we have measured the average and maximum growth rates of the explosive phase for different runs. The results that are plotted in Fig. 3 show weak linear scaling dependences with the resistivity value. The maximum rate is even quasi-independent of the resistivity. This result agrees with previous ones concluding that this phase is driven by an ideal (secondary) nonlinear instability process [1], and can thus be considered as a fast reconnection mechanism. The formation of plasmoids is observed in cases $\eta \lesssim 10^{-4}$. However, they appear as transient structures and disappear during the coalescence of primary islands. Consequently, they do not affect the explosive reconnection phase.

- *Test-particle acceleration*

Energy spectra resulting from our test-particle acceleration computations are plotted in Fig. 4 for two configurations during DTM evolution. The efficiency of the acceleration appears to be four orders of magnitude higher (in energy) during the explosive phase, compared to the Rutherford phase (characteristic of a single tearing mode configuration in absence of plasmoids regime). The conclusion holds whatever is the resistivity value. A power law distribution with a spectral index value of 1.75 is reached, that is however lower than the expected values of $2 - 3$ deduced from solar flares events. Exploring some individual history of highly accelerated particles, we have obtained that the main acceleration mechanism is due the electric field $\mathbf{V} \times \mathbf{B}$ created by the bulk motion with speed $\mathbf{V}$ during the coalescence of the two main islands.

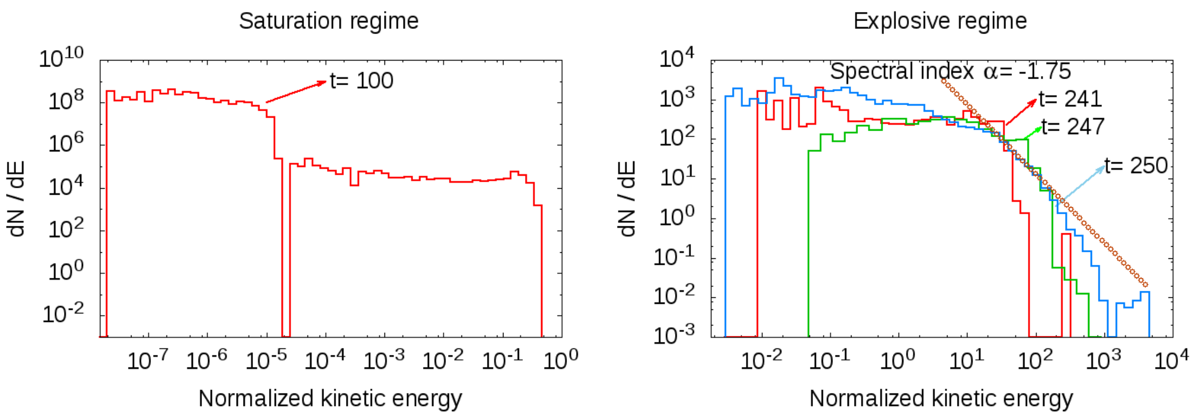

Figure 4: *Energy spectra of test-particles obtained for Rutherford phase at* $t = 100$ *(left panel) and for the explosive phase at* $t = 241, 247, 250$ *(right panel), using MHD configuration for a simulation with* $\eta = 5 \times 10^{-5}$.

Conclusion

The non linear evolution of DTM is shown to be explosive and fast. The time scale of the explosive phase is quasi-independent of the resistivity, corresponding thus to an ideal process. The formation of plasmoids does not affect this behavior as they appear in a transient way. Finally, the coalescence of the main islands is shown to give an efficient acceleration mechanism. Our results indicate that electron/ion kinetic energy values could easily reach $1/100$ MeV during a typical explosive phase.

Acknowledgments

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