Intermittent dynamics of nonlinear resistive tearing modes at extremely high magnetic Reynolds number

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Nonlinear dynamics of the resistive tearing instability in high magnetic Reynolds number (R_m) plasmas is studied by newly developing an accurate and robust resistive magnetohydrodynamic (MHD) scheme. The results show that reconnection processes strongly depend on R_m. Particularly, in a high R_m case, small-scale plasmoids induced by a secondary instability are intermittently generated and ejected accompanied by fast shocks. According to the intermittent processes, the reconnection rate increases intermittently at a later nonlinear stage.

Keywords: tearing instability, high magnetic Reynolds number, MHD, simulation, secondary instability

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The tearing instability is one of the most basic and important mechanism of plasma dynamics both in fusion and astrophysical processes. Particularly, resistive tearing modes have been well investigated theoretically and numerically as the most basic modes of the tearing instability [1, 2, 3]. However, our understanding of the nonlinear dynamics of resistive tearing instability in case of magnetic Reynolds numbers, R_m, as high as the practical systems is still severely limited. A major reason of that is attributed to the fact that the numerical resolution of simulations is too strongly restricted to resolve a thin current sheet, which is believed to be formed in the realistic systems. Therefore, in this study, an accurate and robust resistive MHD scheme is developed, and nonlinear simulations at the highest-ever resolution are carried out in order to find a new dynamic regime of the resistive tearing instability.

First, we develop an accurate, efficient, and robust numerical solver for resistive compressible magnetohydrodynamics (MHD). The Harten-Lax-van Leer-Discontinuities (HLLD) approximate Riemann solver [4], which is one of the promissing shock capturing solver for ideal MHD from the viewpoint of its resolution, robustness, and efficiency, is applied to ideal terms of resistive MHD. Also, higher-order accuracy is achieved by the MUSCL method with limiters. As a divergence cleaning method, hyperbolic divergence cleaning method [5] is adopted. Resistive terms, on the other hand, are calculated by a classical centered finite difference method. In order to confirm the applicability of the present strategy to resistive MHD, severanl numerical tests are performed. As a first test, nonlinear simulations for the resistive tearing mode with a quite small apmplitude are compared with the linear theory [1]. When R_m is large enough (about more than 10^5), the results of both are almost corresponding. We also perform another test of which both the present scheme and the (fully) centered finite difference scheme apply the nonlinear simulation of the tearing instability for a linear force free magnetic field. The results of both are almost the same at an initial stage, while the centered finite difference scheme is brokendown at a later stage. Thus, it is concluded that the present scheme achieves a high degree of the numerical accuracy and robustness even for resistive MHD processes.

Subsequently, nonlinear simulations of resistive tearing modes are performed in a simple 2D slab geometry with uniform resistivity η ($\equiv R_m^{-1}$). The initial condition is given by the Harris equiribrium, $B_{0x} = \tanh(y/\delta)$, where the thickness of the initial current sheet δ is set to 0.5. The simulation box is such that $-12.8 \leq x \leq 12.8$ and $-6.4 \leq y \leq 6.4$. The periodic boundary condition is applied to x direction, while the symmetric condition is adopted for y boundary. In order to resolve the resistive layer sufficiently, non-uniform grid is adopted for y direction. The finest grid spacing is about 0.0102 for x direction and 0.0005 for y direction. In this paper, two cases of relatively low R_m, $R_m = 10^3$, and relatively high R_m, $R_m = 10^4$, are presented in particular. The nonlinear tearing mode at $R_m = 10^3$ steadily grows and is almost saturated as expected from the previous works. On the other hand, it is found that at a high R_m, $R_m = 10^4$, a new dynamics arises after the formation of a thin current sheet at the initial nonlinear stage. Fig. 1 show the current density and mass density distribution around the current sheet. We find that many secondary plasmoids are intermittently created in the thin current sheet and interacted with each other. Through the nonlinear interaction of the plasmoids, various fine structures associated with fast shocks are generated even in the uniform η model. Fig. 2 show the temporal evolution of the maximum electric field in the current sheet induced by the resistivity at both R_m cases. Though

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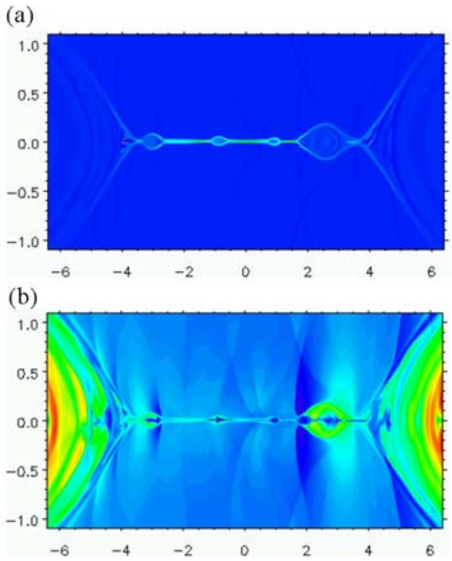

Fig. 1 Distributions of (a) the current density and (b) the density at $R_m = 10^4$

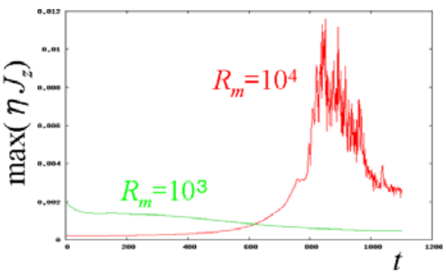

Fig. 2 Time evolution of the maximum resistive electric field in the current sheet at $R_m = 10^3$ (green line) and 10^4 (red line).

multiple X points are advected at $R_m = 10^4$, the resistive electric field is almost considered as the reconnection rate. It is found that the reconnection rate is much enhanced intermittently at $R_m = 10^4$ even though the linear growth rate of the resistive tearing instability is reduced with an increasing of R_m.

The results indicate that the nonlinear dynamics at a high R_m is much different from our conventional understanding based on the linear theory and the simulations at modest value of R_m. It strongly suggests that the realistic MHD dynamics at extremely high R_m (e.g., more than 10^{14} in the solar corona!) is still veiled, and it is likely that some hierarchical MHD dynamics is involved to connect macro-scale plasma evolution and micro-scale kinetic processes.

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