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Magnetic Island Coalescence using Reduced-Hall-MHD Model

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Motivation

Magnetic island coalescence problem has been used to study the magnetic reconnection as the Lorentz force between the current filament drives the reconnection, hence no external driver needed. Simplicity of this problem allows to study the effect of various physical and system parameters on reconnection mechanism. One of such parameter is externally generated shear flow. Shear flow can strongly affect the upstream and downstream plasma flow and hence reconnection rate. Alfvénic or super-Alfvénic shear flows generate MHD-Kelvin-Helmholtz instability (MHD-KHI) which can couple with reconnection driven MHD instabilities such as tearing mode instability or coalescence instability. By using simulation, we study the effect of shear flow on island coalescence instability using an incompressible viscoresistive Hall-MHD model.

Introduction

• 2.5D viscoresistive Reduced-Hall-MHD (VR-RHMHD) equations [1] (in $[z, x]$ Cartesian plane and y-direction is out-of-plane) are,

• $\nabla \cdot \mathbf{u} = 0, \qquad \nabla \cdot \mathbf{B} = 0$

• $\partial_t \omega_y = [\varphi, \omega_y] - [\Psi, J_y] + \hat{\nu}\nabla_\perp^2 \omega_y \qquad (1)$

• $\partial_t \Psi = [\varphi, \Psi] + \hat{\eta}\nabla_\perp^2 \Psi + \varepsilon_H [\Psi, B_y] \qquad (2)$

• $\partial_t B_y = [\Phi, B_y] - [\Psi, u_y] + \hat{\eta}\nabla_\perp^2 B_y + \varepsilon_H [\Psi, J_y] \qquad (3)$

• $\partial_t u_y = [\Phi, u_y] - [\Psi, B_y] + \hat{\nu}\nabla_\perp^2 u_y \qquad (4)$

Here, $\hat{\nu}$ and $\hat{\eta}$ are the normalized viscosity and plasma resistivity respectively, $\varepsilon_H = \frac{c}{\omega_{pi} L}$ is the Hall parameter, ω_{pi} is ion plasma frequency, L is system length scale and $\nabla_\perp^2 \varphi = -\omega_y$, $\nabla_\perp^2 \Psi = -J_y$, $[f, g]_{z,x} = (\partial_z f)(\partial_x g) - (\partial_x f)(\partial_z g)$.

• Equation (1)-(4) are normalized to Alfvénic units i.e. length to system length L_x, velocity to Alfvén velocity $v_A = B_0/\sqrt{\mu_0 \rho}$, time to Alfvénic time $t_A = L_x/v_A$.

• When $\varepsilon_H = 0$, Eq. (1)-(4) reduces to 2.5D Reduced-MHD equations and Eq. (1)-(2) decouples from Eq. (3)-(4).

• The reconnection rate is the reconnecting electric field E_y calculated as total RHS of Eq. (2), at the X-point ($(x, z) = (1, 1)$).

Discussion & Future work

• For in-plane shear flow width $a_v = 2a_B$ (u_y is zero), shear flow weakly destabilize the magnetic island, but strongly effects the coalescence process. Reconnection rate decreases by 50% when $v_0 \sim v_A$.

• With increase in v_0 value, peak value of E_y reduces, pile-up of magnetic flux on both side of reconnecting current sheet also decreases. This can be observed in Fig 2. as the 2nd hump in E_y vanishes with increase in v_0 [2].

• From Fig. 2, for both $\varepsilon_H = 0$ and 0.002, the reduction in peak reconnection rate (E_y) is non-monotonic around $v_0 = 0.5v_A$. However, this behavior is not reported for higher $\hat{\eta}$ value cases [2]. Understanding of this behaviors at lower $\hat{\eta}$ needs further investigation.

• With finite ε_H, both out-of/into-plane flows interact with Hall-generated B_y causing reduction in reconnection rate. Effect of u_y with different values of shear width and orientation along with in-plane flows on reconnection rate is also interesting to investigate.

• For this domain size (L_z) and flow shear width a_v, there is no unstable MHI-KHI mode (A. Miura, Phys. Rev. Lett, 1982). However, for $L_z \geq 5\pi a_V$, MHD-KHI mode will be unstable and can couple with coalescence instability [2]. Role of different a_v values with higher ε_H value, will be investigated in near future.

Simulation Details:

• Eq.(1)-(4) are solved using BOUT++ framework. Respective simulation boundaries along x- and z-direction are conducting and periodic in nature. Simulation domain: $0 \leq x, z \leq 2$. grid size $\Delta z = 0.00048$, Δz=0.00097 ($N_z = 4096, N_x = 2048$), dissipation $\hat{\nu} = \hat{\eta} = 2 \times 10^{-5}$

• Initial profiles for $J_{y0} = (1-\epsilon^2)/(a_B \left[\cosh\left(\frac{x - L_x/2}{a_B}\right) + \epsilon \cos\left(\frac{z}{a_B}\right)\right]^2)$ [2], where $\epsilon = 0.2$ determines the island width, $a_B = 1/2\pi$ determines the simulation domain size as $L_x = L_z = 4\pi a_B = 2$. Initial Shear Flows are supplied through ω_y or u_y profile, as mentioned below.

• **Case 1** ($\varepsilon_H = 0$, $u_y = 0$, ω_y **is non-zero):** Initial current density profile is J_{y0} and vorticity profile as $\omega_{y0} = 1/a_v \times v_0 sech^2\left(\frac{x - L_x/2}{a_v}\right)$, where a_v is the shear flow width and v_0 is the shear flow strength.

• **Case 2** ($\varepsilon_H = 0.002$, $u_y = 0$, ω_y **is non-zero):** Same as case 1.

• **Case 3** ($\varepsilon_H = 0.002$, u_y **non-zero**, $\omega_y = 0$**):** J_{y0} and $u_y = 1/a_B \times u_0 sech^2\left(\frac{x - L_x/2}{a_B}\right)$.

• Equilibrium profiles J_{y0} and $\Psi 0$ are given below.

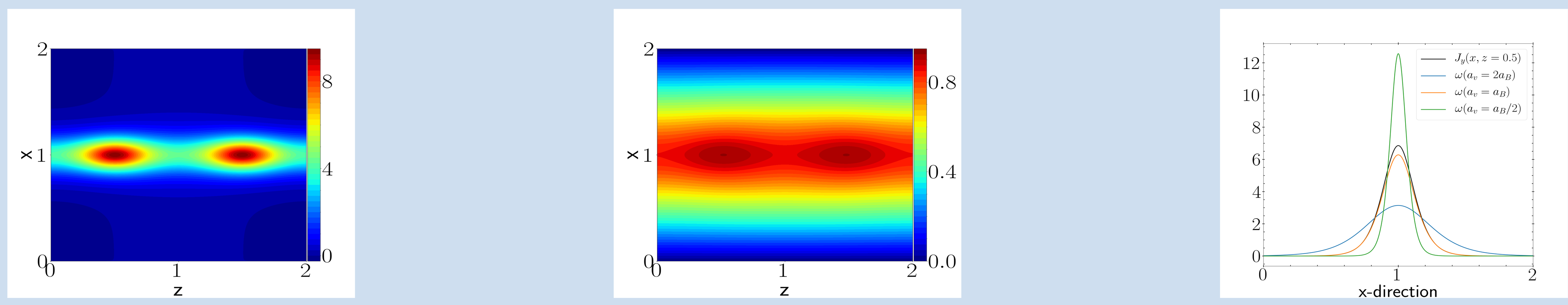

Figure 1. Left-most panel shows initial J_y profile, middel panel shows initial vector potential Ψ profile, and right panel shows different vorticity profile with magnetic island width along $z = 0.5$.

Results from Simulation

• **Case 1 and 2:** Variation in reconnection mechanism and reconnecting electric field E_y is studied by applying in-plane shear flow for flow shear width $a_v = 2a_B$ (flow shear width is larger than magnetic shear/island size) and different flow amplitude $v_0/v_A = 0.2, 0.4, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2$.

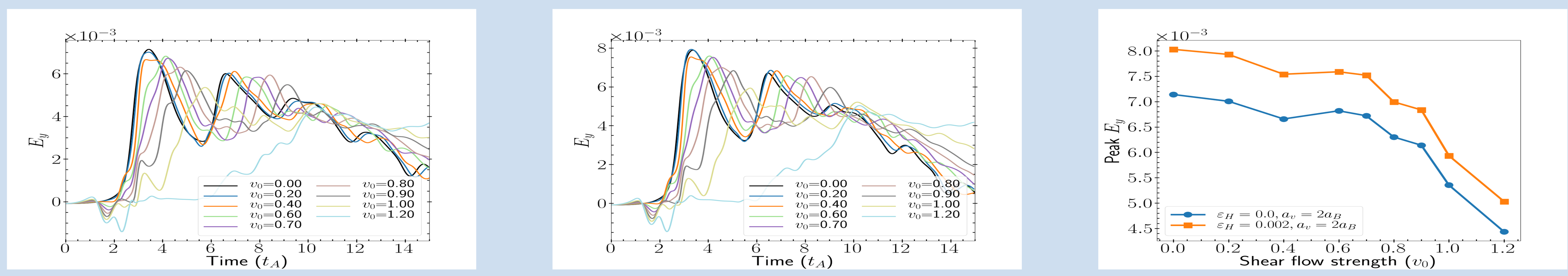

Figure 2. Left and middle panels shows time variation of E_y vs. time for $\varepsilon_H = 0$ and 0.002. For both the plots, $a_v = 2a_B$. Right panel shows variation in Peak E_y value as a function of v_0 for both ε_H=0.002.

• **Case 3:** In this case, finite out-of-plane/into-the-plane flow u_y of different amplitude ($u_0/v_A = -10, -5, +5, +10$) is applied at t=0. Initially supplied u_y generates an out-of-plane B_y (middle panels of Fig. 3). For $u_0 \sim 10v_A$, the magnitude of flow generated B_y becomes same order with that of Hall-effect generated B_y.

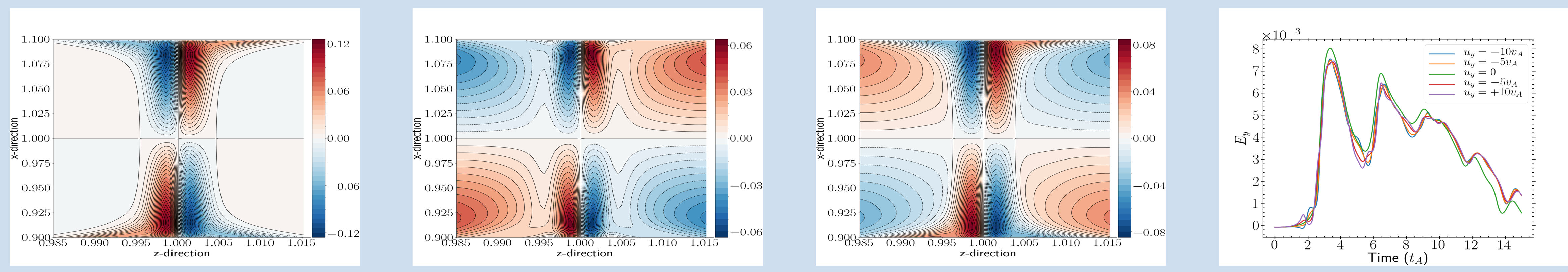

Figure 3. Left panel shows quadrupolar B_y profile around the X-point for $\varepsilon_H = 0.002$. Middle panels shows resultant quadrupolar B_y profile for the case $u_0/v_A = 10, -10$ respectively and $\varepsilon_H = 0.002$ at time t $= 3.4t_A$ (time of peak reconnection rate). Right-most panel shows time evolution of E_y for different u_y values

References/Acknowledgements

(1) D. A. Knoll and L. Chacon, Phys. Rev. Lett. **96**, 135001 (2006).

(2) J. Mahapatra et al., arxiv preprint, arXiv:2102.01312 [physics.plasm-ph] (in communication).

(3) All the simulation are performed on the ANTYA cluster at the Institute for Plasma Research (IPR).