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BRIDGING THE GAP BETWEEN FLUID AND KINETIC MAGNETIC RECONNECTION SIMULATIONS USING AN EFFECTIVE RESISTIVITY CLOSURE

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Abstract. We present a recent study that compares, for the first time, the dynamics of a typical PIC model of relativistic reconnection with the results of resistive RMHD regime adopting a non-constant effective resistivity, which can capture the local enhancement of magnetic dissipation within the reconnecting current sheet. Such "effective resistivity" can not only quantitatively reproduce the typical reconnection rates of kinetic models (which usually are one order of magnitude lower in the RMHD framework), but can do so even at modest grid resolutions and for different levels of magnetization. We then show the results from hybrid RMHD-PIC models that quantify the acceleration of charged particles in the reconnecting pair-plasma, showing once again a remarkable agreement between PIC simulations and RMHD models with our effective resistivity prescription. Our findings provide a general framework to describe more realistically magnetic dissipation and particle acceleration within large-scale simulations of magnetized accretion flows and jets.

Keywords: magnetic reconnection, MHD, relativistic processes, acceleration of particles, numerical methods

1 Introduction

Magnetic reconnection is one of the most important physical processes that powers many high-energy transient phenomena (e.g. flares from black hole magnetospheres, blazar jets, and fast radio bursts), as the dissipation of magnetic fields can efficiently accelerate charged particles and thus lead to the production of the observed non-thermal emission. Numerical models adopting a fully-kinetic approach can self-consistently capture the properties of magnetic dissipation during a reconnection event, but their high computational cost makes the study of the large-scale dynamics extremely challenging. On the other hand, relativistic MHD models are instead widely used to describe the accretion/ejection of matter and magnetosphere dynamics on scales set by an astrophysical compact object, but they generally can't reproduce a self-consistent dissipation mechanism, being limited by either numerical dissipation or an explicit resistivity parameter not constrained by the microphysics.

2 Effective resistivity and numerical setup

Based on a relativistic Ohm's law for a pair plasma (Hesse & Zenitani 2007), 2D PIC simulations of relativistic reconnection (Selvi et al. 2023) show that the electric field in the fluid comoving frame e_z (i.e. the non-ideal component) is dominated by the yz ram-pressure contribution. This result can be exploited to construct an *effective resistivity* suitable for a fluid numerical model as (Bugli et al. 2025) $\bar{\eta}_{\rm eff} = (\bar{\delta}_u/\bar{\rho})\sqrt{\left(\bar{\delta}_u \partial_{\bar{y}} \bar{v}_y\right)^2 + \bar{e}_z^2}$, where $\bar{\eta}_{\rm eff}$ is the fluid resistivity parameter, $\bar{\rho}$ is the rest mass density, $\bar{v}_y$ is the velocity component transverse to the initial current sheet, $\bar{e}_z$ is the electric field in the fluid comoving frame. The quantity $\bar{\delta}_u$ is an *effective skin depth* corresponding to the physical units employed for lengths and mass density by the code, thus introducing

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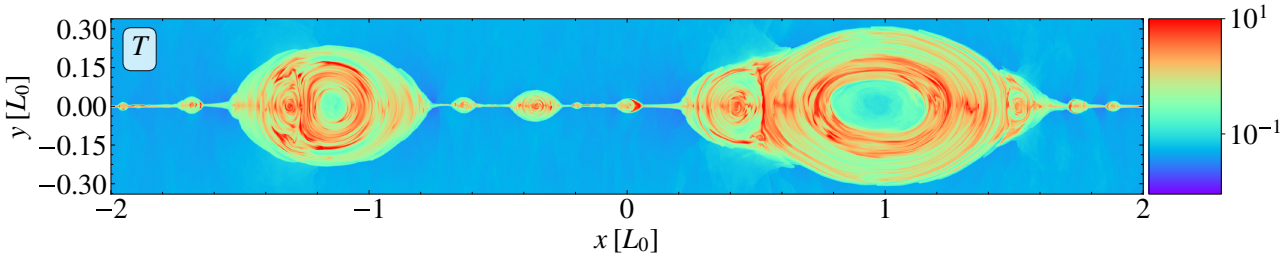

Fig. 1. Temperature distribution during the plasmoid instability phase for a RMHD model with effective resistivity.

a new characteristic scale in the fluid model. We implemented the effective resistivity in the resistive relativistic magnetohydrodynamics (ResRMHD) module of the `PLUTO` code (Mignone et al. 2007) and tested it on a standard Harris current sheet in pressure-balanced equilibrium (Bugli et al. 2025) with length $L_0 = 1$ and width $a = 0.01$. We adopt an upstream *cold* magnetization $\sigma_0 = \{1, 4, 10\}$, density $\rho_0 = 1$, thermal to magnetic pressure ratio $\beta_0 = 0.01$, effective skin depth $\bar{\delta}_u = 0.02$, and a numerical box with sizes $[-2L_0, 2L_0] \times [-80\sqrt{\sigma_0}a, 80\sqrt{\sigma}a]$, to which we impose periodic and reflective boundary conditions along x and y, respectively.

3 Results and future prospects

All our simulations lead to fast reconnection on dynamical time-scales, with a clear onset of the plasmoid instability that fragments the current sheet into merging magnetic islands (Fig. 1). By producing corresponding Particle-In-Cell (PIC) simulations using the `ZELTRON` code (Cerutti et al. 2013), we verified that our effective resistivity formulation is capable of quantitatively reproducing the reconnection rates ($\beta_{\rm rec} \simeq 0.1$) and the general dynamics of fully kinetic models. While a constant resistivity prescription needs very high Lundquist numbers ($S \sim 10^6$, thus low numerical dissipation) to trigger the onset of the *ideal tearing mode* (Del Zanna et al. 2016), our model captures the kinetic nature of dissipation within the current sheet already at modest resolutions. We also quantified the efficiency of particle acceleration within our models by running hybrid ResRMHD-PIC simulations where we injected and evolved electrons according to $d(\Gamma_p \bar{\boldsymbol{v}}_p)/d\bar{t} = \bar{\delta}_u^{-1}(\bar{\boldsymbol{E}} + \bar{\boldsymbol{v}}_p \times \bar{\boldsymbol{B}})$, where $\boldsymbol{v}_p$ is the particle velocity, Γ_p its Lorentz factor, $\boldsymbol{E}$ is the electric field, and $\boldsymbol{B}$ is the magnetic field. We once again find a remarkable agreement between the spectra obtained with our effective resistivity prescription and the PIC models, both in term of slope and cut-off energy ($\sim \sigma_0$). On the other hand, models with constant resistivity tend to grossly overestimate the amount of high-energy particles accelerated and produce clearly nonphysical spectra (i.e. almost flat across orders of magnitudes in Lorentz factor).

In conclusion, our effective resistivity prescription allows to quantitatively capture, for the first time, fundamentally kinetic effects in ResRMHD models of magnetic reconnection. In the future we plan on including in our models a guide field (Moran et al. 2025), extending them to 3D by menas of high-order schemes (Berta et al. 2024; Mignone et al. 2024), and testing it in resistive large-scale jet simulations (Mattia et al. 2023).

Our figures have been produced using the `PyPLUTO` tool (Mattia et al. 2025). Thank you to the organizers of the SF2A 2025!

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