Optimal initial perturbations for current sheet simulations

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Introduction

Magnetohydrodynamic (MHD) simulations are an important tool to model the plasma structures observed in the solar atmosphere. When starting from an equilibrium, simulations are usually initialised with an initial perturbation of the magnetic field or fluid velocity. In the former case, this is an analytic expression satisfying div(**B**) = 0, whereas in the latter case a common choice is simply random noise. Though both methods generally work well, it raises a few questions: does the initial perturbation affect the evolution? What if we perturb the system with one (or a superposition) of its natural oscillations (i.e. linear eigenmodes)? What is the effect in the presence of competing instabilities, e.g. in solar current sheets?

The Legolas and MPI-AMRVAC codes

In this study we combine two codes: Legolas and MPI-AMRVAC. The former is a linear MHD code that perturbs density, velocity, temperature, and magnetic field about a 1D-varying equilibrium, imposes a Fourier form for the perturbed quantities,

$$f_1(\boldsymbol{x}) = \hat{f}_1(x)\,\exp\left[\mathrm{i}\left(k_y y + k_z z - \omega t\right)\right]$$

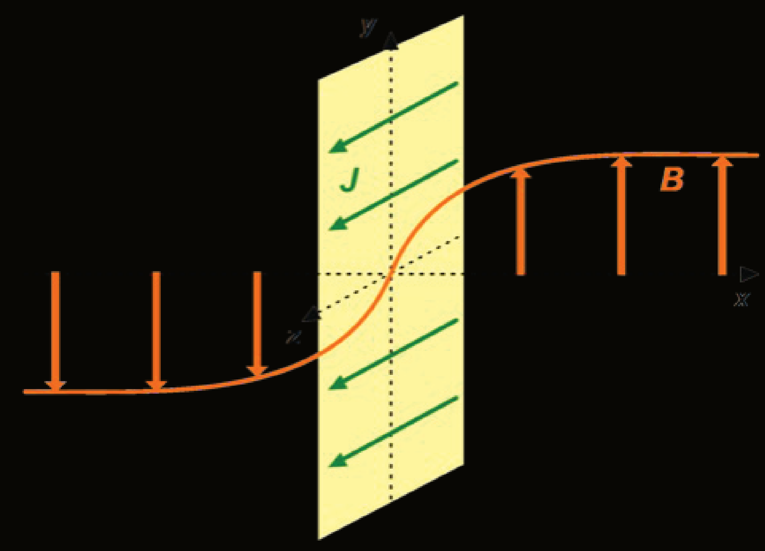
and solves for the frequency ω and amplitudes $\hat{f}_1(x)$. This offers a computationally inexpensive look at the linear dynamics.

MPI-AMRVAC is a non-linear, time-evolving simulation code. In this work, we rely on its MHD module to simulate the configuration studied with Legolas in 2D and 3D beyond the linear stage for varying initial perturbations of the equilibrium. A selection of Legolas solutions are used as initial perturbations.

Legolas

MPI-AMRVAC

Harris sheet configuration



A current sheet is a plane with a certain electric current density associated to a magnetic field reversal across that plane. To obtain a constant total pressure, the magnetic pressure is balanced by either density or temperature. Here, the density is constant and magnetic pressure is balanced with an appropriate temperature profile. The Harris sheet is unstable to resistive and thermal instabilities.

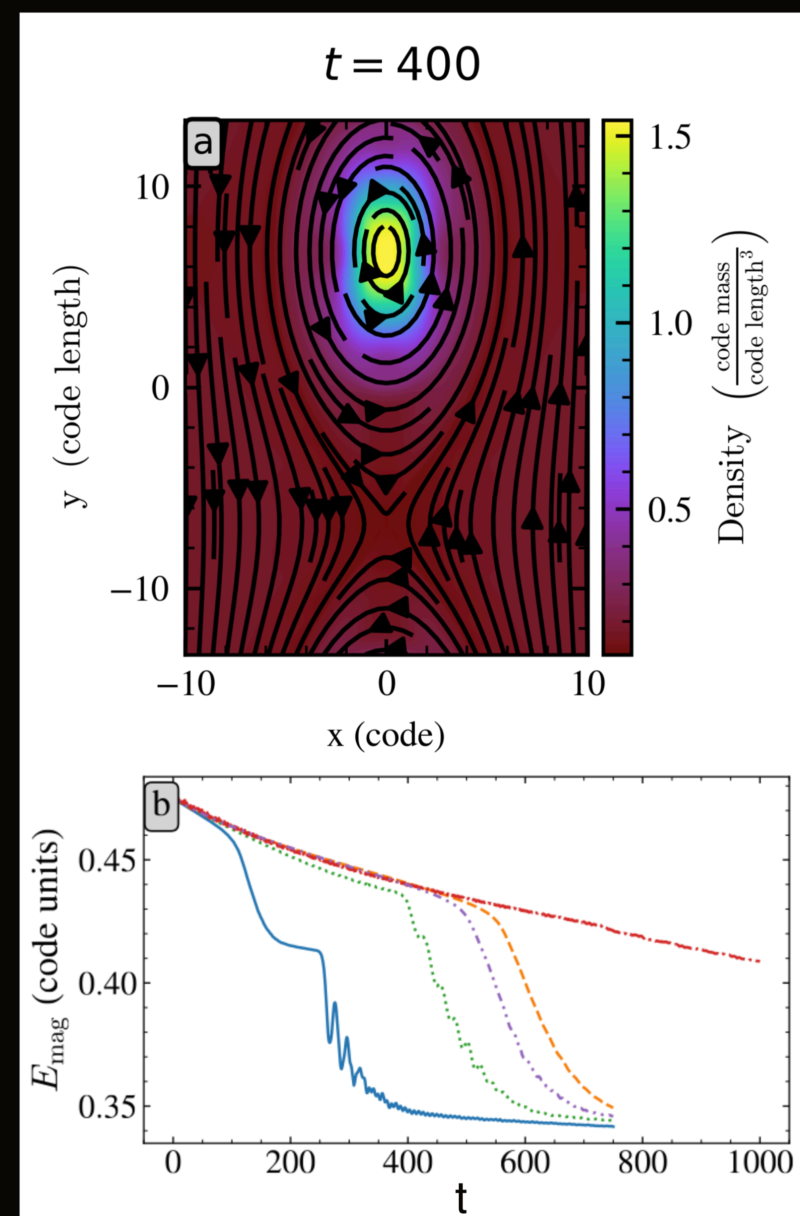
<u>Force-free variant</u>: In the force-free variant, the magnitude of the magnetic field remains constant in the polarity reversal region, such that density and temperature are constant in this case.

$$\boldsymbol{B}_0(x) = B_0\,\tanh\left(\frac{x}{a}\right)\,\hat{\boldsymbol{e}}_y + \underbrace{B_0\,\mathrm{sech}\left(\frac{x}{a}\right)\,\hat{\boldsymbol{e}}_z}_{\text{Force-free addition}}$$

Role of the initial perturbation

In the absence of thermal effects, the resistive Harris sheet is only unstable to the tearing instability, which reduces the configuration's magnetic energy by forming magnetic islands, shown to the right. Using MPI-AMRVAC, we simulated this evolution 5 times, where each simulation was initialised with a different perturbation:

1. Tearing instability (TI, blue)
2. Fast waves (FW, orange)
3. TI + FW (green)
4. Analytic magnetic field perturbation (red)
5. Random velocity noise (purple)

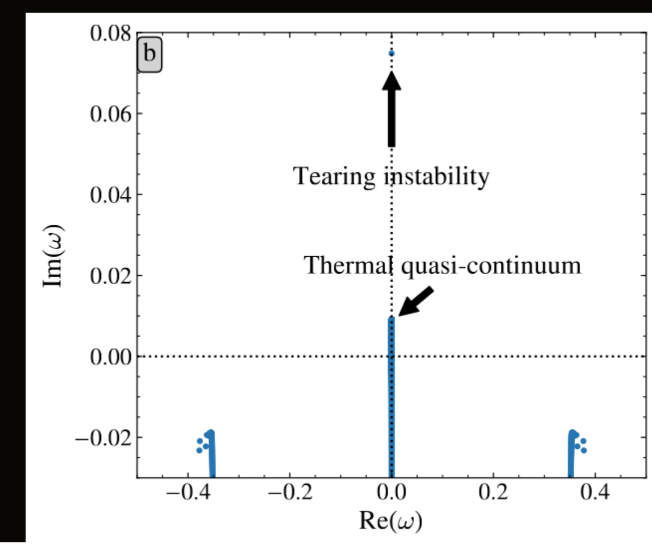


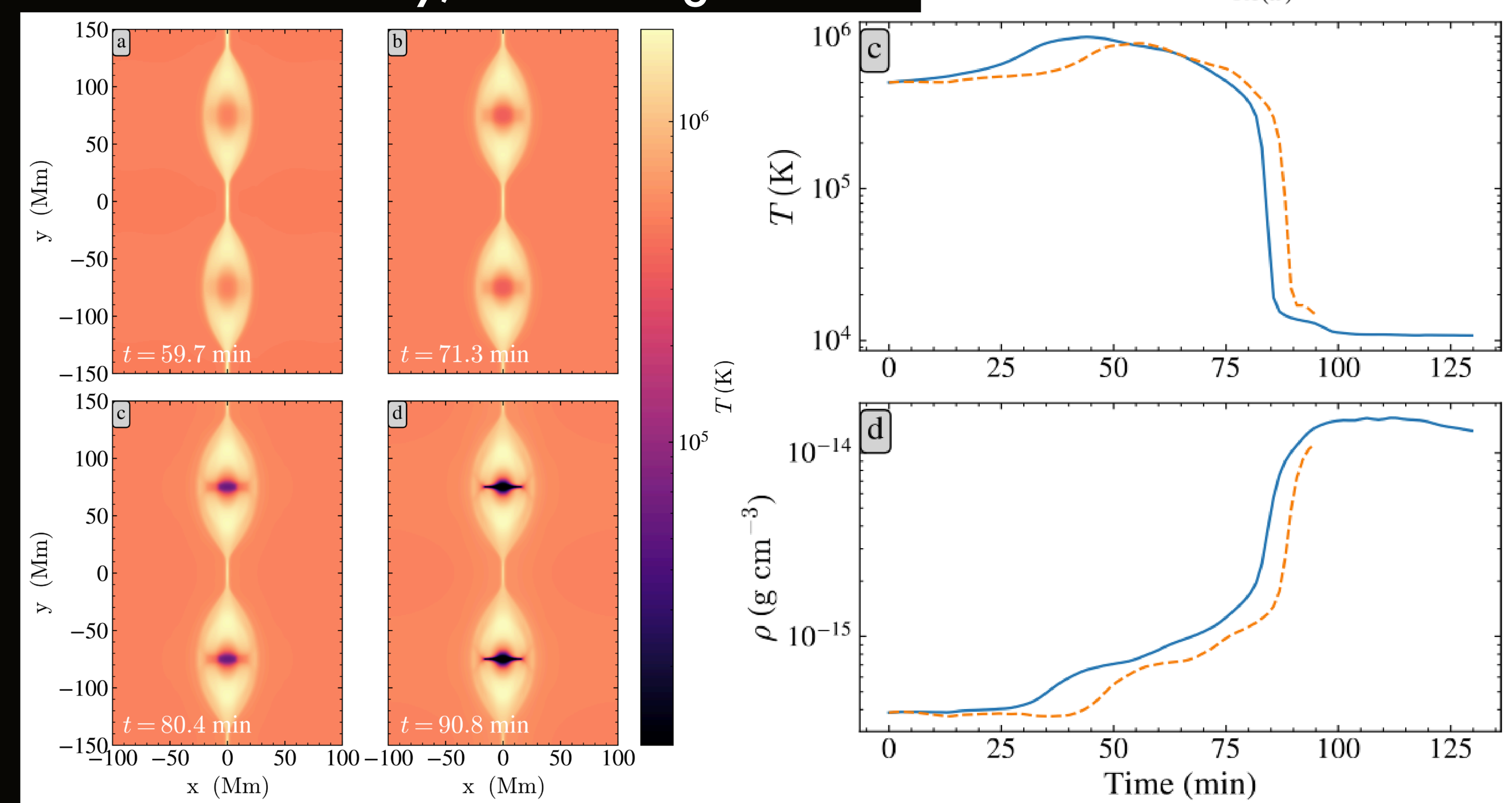
De Jonghe & Russell (2024, under review)

Each simulation was observed to evolve towards the same single-island state shown above for case 1. However, the time at which each simulation reached this configuration varied drastically, as shown in terms of the magnetic energy in the bottom figure.

Solar current sheets

In the solar corona, current sheets are also unstable to thermal instabilities when thermal conduction, radiative cooling, and heating are accounted for. This can be seen in the eigenfrequency spectrum (calculated with Legolas) shown below. For this configuration, we performed two 3D simulations: one initialised with the tearing instability (blue), and one with a superposition of 3 arbitrary thermal quasi-continuum modes (dashed orange). In both cases, the simulation developed flux ropes (helical magnetic field structures) before a thermal runaway effect caused cool and dense structures to form along the flux rope axes. Tracing the temperate and density at condensation sites in both simulations, we observe that the simulation initialised with the thermal modes lags about 5 min behind on the simulation with the tearing mode. This is presumably due to the growth rate difference of these modes in the early, linear stage.





De Jonghe & Sen (2024, accepted)

Summary

Using the non-linear MHD code MPI-AMRVAC, the evolution of a Harris current sheet was modelled for different initial perturbations. Rather than applying traditional, arbitrary perturbations, the initial perturbations were linear solutions of the system calculated with the Legolas code. The choice of initial perturbation affects how quickly the simulation reaches the non-linear stage. Therefore, perturbing with the configuration's fastest growing mode significantly reduces the computation time spent in the linear stage.

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