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# Proton temperature anisotropy and current sheet stability: 2-D hybrid simulations


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**Abstract.** The solar wind is a weakly collisional non homogeneous plasma; gradients associated to density, velocity shears and current sheets are often observed. In situ observations also show that the solar wind plasma is far from thermal equilibrium and particle distribution functions are not isotropic. The presence of a temperature anisotropy can be the source of free energy for kinetic instabilities and their unstable fluctuations may grow and propagate in the plasma. However, how these fluctuations evolve in a non homogeneous medium and how they interact and influence local coherent structures, is still an open question. We report preliminary numerical simulations that describe the evolution of current sheets in a non thermal plasma, focusing on the interaction between kinetic effects driven by a proton temperature anisotropy and magnetic reconnection processes.



**Keywords:** Solar Wind; Kinetic Instabilities; Magnetic Reconnection; Numerical Simulations
**PACS:** 52.35.Py, 52.35.Vd, 96.50.Ci, 52.65.Rr


## INTRODUCTION

Weakly collisional plasmas as the solar wind, have the tendency to develop temperature anisotropies [e.g., 1]. In situ measurements of solar wind distribution functions present departures from the local thermal equilibrium. Proton distributions often show the presence of a temperature anisotropy with respect the ambient magnetic field ($T_\perp \neq T_\|$)[2]. Statistical studies of the properties and evolution of the proton distributions suggest that instabilities driven by a temperature anisotropy are at work in both the slow and fast wind [3, 4, 5]. Moreover, enhanced magnetic fluctuations associated to these instabilities are observed in the solar wind plasma [6] (see also the paper by *Wicks et al.* [7] in this volume).

Figure 1 reports slow wind observations ($v_{sw} < 600$ km/s) from the WIND spacecraft at 1 AU, after [3]. The histogram encodes the observational counts of the proton temperature anisotropy $T_\perp/T_\|$ as a function of the proton parallel beta $\beta_\| = 8\pi n k_B T_\| / B_0^2$. The distribution of data in this parameter space shows apparent boundaries, suggesting the presence of mechanisms shaping the amount of anisotropy as a function of the plasma thermodynamic conditions. Such observational boundaries are in good agreement with the limits of kinetic instabilities driven by proton anisotropy predicted by the Vlasov linear theory (in the figure the different lines encode the level of constant growth rate $\gamma = 10^{-3}\Omega_{cp}$, where $\Omega_{cp}$ is the proton cyclotron frequency, for different anisotropy driven instabilities), suggesting that these processes play a role in constraining the observed anisotropy. Note that we have included the influence of 5% alpha particles in the linear computation of thresholds [1].

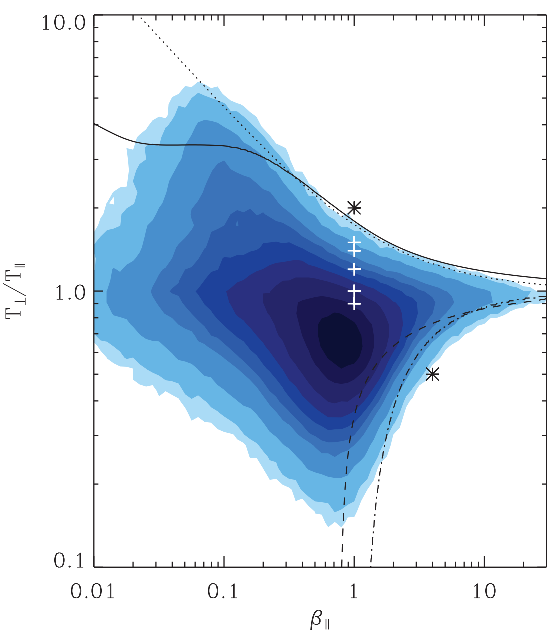


**FIGURE 1.** Observational counts of proton anisotropy as a function of the proton beta at 1 AU (WIND data). Ion-cyclotron (solid), mirror (dotted), parallel (dashed) and oblique (dash-dotted) fire hose linear instability thresholds are reported. Crosses and asterisks encode the initial conditions of simulations discussed.

At the same time, discontinuities of the magnetic field


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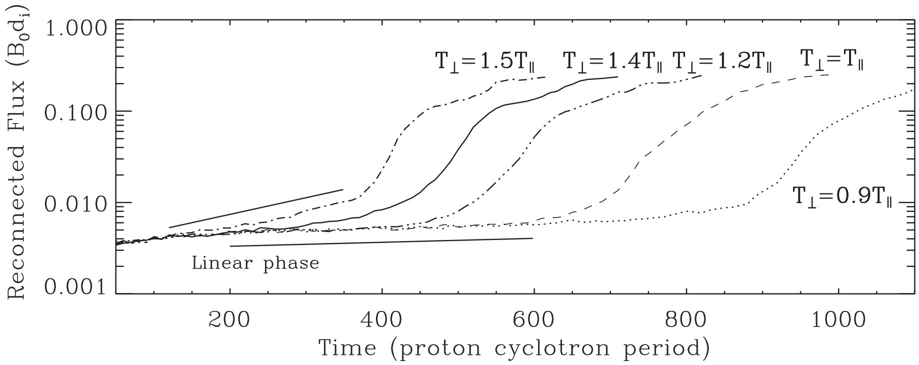


**FIGURE 2.** Time history of the normalized reconnected flux for simulations with different initial proton temperature anisotropy.

are often observed in the solar wind, possibly associated to current sheets and reconnection sites [8]. In particular, a recent study [9] has shown that there is a possible correlation between the distribution of discontinuities and that of proton anisotropies. This motivates a deeper investigation of the connection between these two solar wind aspects and related physical processes.

In this paper we briefly discuss some of the properties of current sheets in anisotropic plasmas, focusing on their interaction with small scale dynamics and kinetic processes. We report results from 2-D hybrid simulations: we first focus on the evolution of the tearing instability in the presence of proton temperature anisotropy in the current sheet region, then we introduce modifications by unstable waves generated in the background plasma by anisotropy driven kinetic instabilities and we discuss the overall consequences of these processes on the system stability.

## TEARING INSTABILITY WITH ANISOTROPIC PROTONS

It is well known that current sheets can be unstable to filamentation of the current, i.e. tearing instability. Some authors have studied the role of temperature anisotropy in driving this instability in the past [e.g. 10, 11]. In particular, it was found [12] that in the presence of a $T_\perp > T_\parallel$ proton anisotropy, the growth rate of the tearing instability is expected to increase with respect the isotropic case. On the other side, it was also suggested that the instability can be significantly suppressed if the opposite anisotropy $T_\perp < T_\parallel$ is present in the current sheet. Here such a picture is recovered through numerical simulations. We use a two-dimensional hybrid code [13], describing ions as particles and electrons as a massless charge neutralizing fluid. We initialize the system using a Harris equilibrium model for the magnetic field:

$$B_y(x) = B_0 \tanh(x/l) \tag{1}$$

$$n(x) = n_{cs}\mathrm{sech}^2(x/l) + n_b \tag{2}$$

with a maximum density $n_0 = 1$ at the current sheet. We add a background proton population with $n_b = 0.2n_0$ uniformly in the box. Units of space and time in the simulations are the ion inertial length $d_i = c/\omega_{pi}$ ($\omega_{pi}$ is the plasma frequency) and the inverse of the proton cyclotron frequency, $\Omega_{cp}^{-1}$, respectively. The adopted simulation box is long 50 $d_i$ in the $x$ direction and 200 $d_i$ in the $y$ direction, with a 100x200 grid and spatial resolution $\Delta x = 0.5$ and $\Delta y = 1$; we use $10^3$ particles per cell. The box has periodic boundaries in both dimensions, thus containing 2 current sheets of width $l = 1.5d_i$.

Starting from this initial configuration we have tested the stability of the system for different cases. First, in the background plasma $\beta_\parallel = 1$ and $\beta_e = 0.5$ for electrons, while the temperature anisotropy of protons within the current sheet is systematically varied through different runs. In all cases the current sheets are found to be unstable for tearing instability; this drives the filamentation of the current and the formation of magnetic islands, which then coalesce during the nonlinear phase of the instability. However the timescale of the process is observed to be strongly influenced by the level of proton anisotropy. Figure 2 reports the time history of the normalized reconnected flux for simulations with different initial conditions of $T_\perp/T_\parallel$. Note that in the figure the linear phase of the instability ("tearing") corresponds to the flatter initial part, and that the strong increase of the reconnection identifies the nonlinear phase, with large amplitude island growth and merging. The results are in very good agreement with the predictions by [12]: in the presence of a $T_\perp > T_\parallel$ proton anisotropy, the growth rate of the tearing instability is found to increase with respect the isotropic case. On the other side, the tearing instability can be significantly weakened with the opposite anisotropy $T_\perp < T_\parallel$. Moreover, this confirms that our setup is suitable for studying couplings between the evolution of the current and processes connected to particle anisotropies. We are now interested on how the picture can be further changed by the fact that temperature anisotropies may also drive kinetic instabilities.

## ROLE OF FLUCTUATIONS GENERATED BY KINETIC INSTABILITIES

When extending the investigation to larger temperature ratios the plasma can become unstable with respect kinetic instabilities driven by enhanced thermal anisotropies (see Figure 1). Is then interesting to investigate what happens when the ambient anisotropy is such to destabilize these linear instabilities and what are the consequences on the evolution of current sheets.

Starting from the same magnetic configuration as in previous section, we have performed simulations where the temperature anisotropy is not limited to the current sheet region, as in previous runs, but extended to the background plasma. We considered cases of opposite temperature anisotropy. The adopted initial conditions are: $\beta_\parallel = 1$ and $T_\perp/T_\parallel = 2$, and $\beta_\parallel = 4$ and $T_\perp/T_\parallel = 0.5$; these are predicted unstable by linear theory (predicted dominant instabilities are ion-cyclotron and parallel fire hose respectively) and are encoded by asterisks in Figure 1. Note that when the plasma is studied in a regime of stability for the background protons (crosses in Figure 1) no qualitative differences are observed in the evolution of the tearing instability with respect to the cases already reported in Figure 2.

On the contrary, when the initial anisotropy of the background is beyond the instability thresholds, in the early stages of the simulation we observe the generation of unstable fluctuations that develop in the region of the locally homogeneous magnetic field $B_0$ bounded by the current sheets. Left panels of Figure 3 report the $B_z$ fluctuations transverse to the ambient $B_y$ field and which are associated to ion-cyclotron (top) and fire hose (bottom) instabilities. These waves are generated by the free energy associated to the anisotropic proton distribution functions and lead to the isotropization of the plasma through particle scattering [e.g., 1]. The associated growth rates and wavenumbers are found to be consistent with the prediction from the linear Vlasov theory, with some deviations likely due to the assumption of homogenous plasma in the theory, while our simulations contain discontinuities. Moreover, as soon as these fluctuations are generated, they start to perturb and modulate the current sheet profiles, as shown by the profile of the out-of-the-plane current $J_z$ reported in the right panels.

We find that in the case of the ion-cyclotron instability, this modulation is able to trigger the tearing of the current; thanks to the symmetry imposed to the plasma motion by the fluctuations at the two sides of the sheet, the driven perturbation of the current is favorable to the tearing mode so that the instability is efficiently triggered. Moreover, since the timescale of the trigger is set by the growth rate of the ion-cyclotron instability (thus by the level of anisotropy in the background) and this may be shorter than the linear tearing timescale, the resulting collapse of the current can be significantly accelerated with respect to the case of stable plasma (Figure 4).

On the contrary, when the fire hose instability is excited, the observed modulation of the current sheets is of the kink-type and does not trigger a tearing mode. As shown in the right bottom panel of Figure 3, these are observed to oscillate passively under the effect of the fire hose mode. Such oscillations are then damped, as soon as the fire hose mode is later reabsorbed by the plasma; as a consequence, after this oscillatory stage, the current sheets remain stable for a remarkable long time.

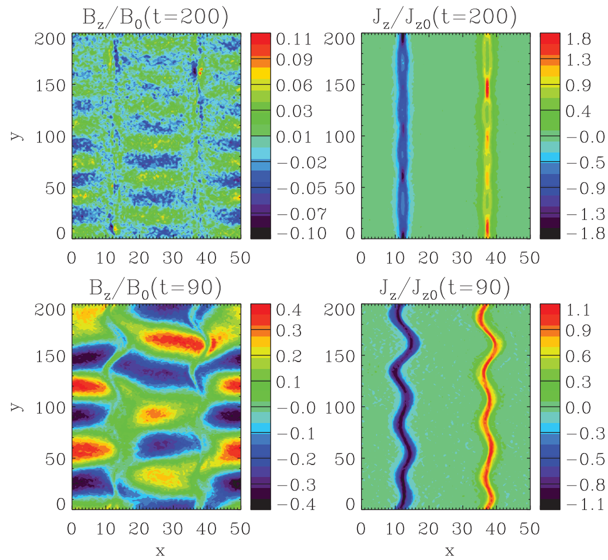


**FIGURE 3.** Evolution of transverse magnetic field fluctuations $B_z$ (left) and out-of-the-plane current $J_z$ (right) during simulations where initial conditions are set unstable for ion-cyclotron (top) and fire hose (bottom) instabilities.

## CONCLUSION

In summary, we have reported simulations of current sheets embedded in an anisotropic plasma. We have tested the stability of the initial Harris equilibrium to the temperature ratio that characterizes protons inside and outside the sheets. In agreement with previous works [12, 14], we find that the temperature anisotropy plays an important role in determining the stability of the current with respect the tearing instability. A $T_\perp > T_\parallel$ condition leads to faster tearing, while the opposite $T_\perp < T_\parallel$ condition has a stabilizing effect (Figure 2).

The development of kinetic instabilities that are driven when these temperature anisotropies are distributed in the background plasma, changes further the properties of the system. We have found that when staring from initial conditions that are predicted unstable by the Vlasov homogeneous linear theory, kinetic instabilities like fire hose and ion-cyclotron can develop and growth also in non homogeneous plasmas, as in our simulations. This result supports the idea that such processes can be at work in the solar wind, that is characterized by both non thermal distributions and coherent structures. We have shown that ion-cyclotron fluctuations, generated when $T_\perp > T_\parallel$, are able to trigger the destabilization of the current and drive a tearing instability that emerges more rapidly than it does in the case in which the ion-cyclotron modes are not excited. On the other hand, we have also shown that fire hose fluctuations that are generated by a $T_\perp < T_\parallel$ anisotropy, even if with large amplitudes, are not able to trigger the instability of the current. In this case, due to the symmetry of those modes, the observed deformation is of the kink-type and does not produce favorable conditions for tearing. As a consequence the current sheets remain stable even when such fluctuations are later dissipated, and remarkably, for a longer time than the isotropic or fire hose stable, case. We discuss more in details the properties of the observed dynamics, including the wavenumber scaling of the tearing and its dependence on the thickness of the current sheets, in a dedicated paper (*Matteini et al.* "Proton temperature anisotropy and magnetic reconnection in the solar wind: effects of kinetic instabilities on current sheet stability", *submitted to ApJ*).

We propose that a similar evolution may take place in the solar wind, where both conditions of $T_\perp > T_\parallel$ and $T_\perp < T_\parallel$ for protons are observed, and kinetic instabilities, like fire hose and ion-cyclotron, are believed to play a role in regulating such proton temperature anisotropy along the solar wind expansion [3, 4, 5, 6]. Our results demonstrate that unstable fluctuations generated by kinetic instabilities can importantly influence the evolution of the magnetic structures in a plasma, thus actively contributing to the relative occurrence of reconnection events in the solar wind, and providing possible explanations for the statistical distribution of discontinuities observed in situ. In this framework, data analysis of small scale fluctuations and particle anisotropies should be complemented with local wind structure informations. The interaction between particle properties and the evolution of small scale magnetic structures, as described in this work, will be more deeply investigated with the help of measurements from the future heliospheric explorations, as Solar Orbiter and Solar Probe Plus, where combined particle and field high resolution observations are planned.

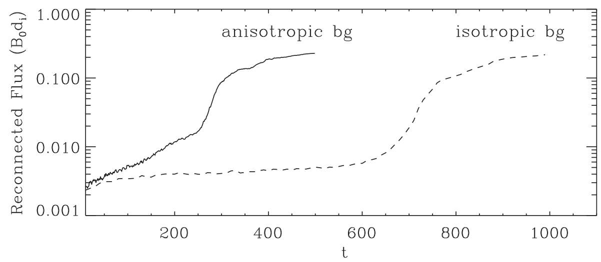


**FIGURE 4.** Time history of reconnected flux in case of (dashed) isotropic and (solid line) anisotropic, ion-cyclotron unstable, proton background.

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