Collisionless Kelvin-Helmholtz instability and vortex-induced reconnection in the external region of the Earth magnetotail

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Abstract. In a magnetized plasma streaming with a non uniform velocity, the Kelvin-Helmholtz instability plays a major role in mixing different plasma regions and in stretching the magnetic field lines leading to the formation of layers with a sheared magnetic field where magnetic field line reconnection can take place. A relevant example is provided by the formation of a mixing layer between the Earth's magnetosphere and the solar wind at low latitudes during northward periods. In the considered configuration, in the presence of a magnetic field nearly perpendicular to the plane defined by the velocity field and its inhomogeneity direction, velocity shear drives a Kelvin-Helmholtz instability which advects and distorts the magnetic field configuration. If the Alfvén velocity associated to the in-plane magnetic field is sufficiently weak with respect to the variation of the fluid velocity in the plasma, the Kelvin-Helmholtz instability generates fully rolled-up vortices which advect the magnetic field lines into a complex configuration, causing the formation of current layers along the inversion curves of the in-plane magnetic field component. Pairing of the vortices generated by the Kelvin-Helmholtz instability is a well know phenomenon in two-dimensional hydrodynamics. Here we investigate the development of magnetic reconnection during the vortex pairing process and show that completely different magnetic structures are produced depending on how fast the reconnection process develops on the time scale set by the pairing process.

1. Introduction
Magnetic field line reconnection is one of the most important and basic physics processes in a magnetized plasma [1], capable at the same time of restructuring the large scale topology of the magnetic field and of affecting the global energy balance of the system by transforming the magnetic energy related to the plasma current inhomogeneities into plasma kinetic and/or thermal energy. In fact magnetic reconnection is considered to be the driver of the most important energetic phenomena observed in laboratory plasmas, e.g., in thermonuclear fusion devices, and in space plasmas, e.g., in the solar atmosphere or in the Earth’s magnetosphere.

The research effort in the understanding of the physics underlying magnetic reconnection in high temperature plasma regimes has progressed remarkably in recent years but magnetic reconnection still remains a formidable challenge concerning the problem of why and under what conditions the system enters a reconnection phase and how this process evolves nonlinearly. Recent studies have focussed in particular on the so-called “fast” magnetic field line reconnection since in low collisionality or collisionless plasma regimes this process is expected to occur on time scales that do not exceed by large factors the dynamical time scales of the plasma configuration.
as determined e.g., within the ideal magnetohydrodynamic description. When current layers are formed that have widths of the order of the ion skin depth $d_i \equiv c/\omega_{pi}$, with $\omega_{pi}$ the ion plasma frequency, ions inside these current layers decouple their motion from the evolution of the magnetic field. Per se this decoupling is not sufficient to allow for magnetic reconnection which requires electron decoupling. Electrons decouple from the magnetic field inside a thinner region that, depending on the plasma parameters, has a width determined either by a nonvanishing resistivity or by kinetic (phase space) effects, or, as is the case in the fluid electron model description adopted here, by finite electron inertia effects. The large spatial separation between these two decoupling regions allows magnetic reconnection to grow at a faster rate [2, 3, 4, 5, 6].

Theoretically, two different approaches are routinely used when investigating magnetic reconnection. Magnetic reconnection is described either as an initial value problem in a magnetic configuration with an inhomogeneous current distribution [7, 8] where a reconnection instability develops spontaneously (in a configuration that allows for modes with a positive delta prime in the jargon of one-dimensional reconnection studies) or a boundary value problem is considered where reconnection is driven in a “stable” magnetic configuration by an external driver, e.g., by injecting Alfvén waves [9] or by imposing a stationary plasma inflow that pushes regions of different magnetic polarity (regions where at least one on the magnetic field line components reverses its sign) one against the other [10, 11]. In both cases the system is ”prepared” ad hoc in order to develop a reconnection process.

Observationally, the Earth environment is a laboratory of excellence for the study of the physics of magnetic reconnection because of the importance of this process in the dynamics and shaping of this region and because of the increasing wealth of data of ever improving quality on the electromagnetic field profiles and on the particle distribution functions obtained in situ. The understanding of the phenomena related to collisionless magnetic reconnection have made great progress due to the results obtained by space missions like Geotail and Cluster. Satellite measurements have given in situ evidence of reconnection in the magnetotail [12, 13, 14], in the magnetosheath [15] and even in the turbulent plasma in the Earth’s bow shock [16]. The key role of whistler waves has been demonstrated in a “fast” reconnection event reported by the Cluster quartet [17], in agreement with theoretical predictions [18, 19]. Of special relevance is the first evidence of the presence in the magnetotail of coherent magnetic structures (defined as magnetic islands) with typical dimensions of the order of the ion inertial length and their link to the generation of energetic supra-thermal electrons [20]. Magnetic island type structures embedded in a current sheet in the magnetopause were reported in Refs. [21, 22] starting from Cluster data and using a magnetohydrostatic reconstruction technique. In addition, a denser plasma layer was observed on the Earth side of these structures. This denser layer is a signature of a solar wind plasma entry inside the magnetosphere.

In a magnetized plasma streaming with a nonuniform velocity, the Kelvin-Helmholtz instability plays a major role in mixing different plasma regions and in stretching the magnetic field lines leading to the formation of layers with a sheared magnetic field where magnetic field line reconnection can take place. If the Alfvén velocity associated to the in-plane 1 magnetic field is sufficiently weak with respect to the variation of the fluid velocity in the plasma, the Kelvin-Helmholtz instability generates fully rolled-up vortices which advect the magnetic field lines into a complex configuration, causing the formation of current layers along the inversion curves of the in-plane magnetic field component. Since the plasma dynamics is essentially driven by the vortex motion, the reconnection events that are produced in these layers are usually denoted as vortex-induced reconnection [23, 24, 25, 26, 27].

Satellite measurements have provided clear evidence of the presence of rolled-up vortices at the flank of the magnetopause [28]. In this region, the velocity shear between the magnetospheric

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1 In the plane defined by the velocity and by the plasma inhomogeneity directions
and the solar wind plasmas generates hydrodynamic Kelvin-Helmholtz vortices which tend to pair in their non linear regime [29]. This provides an efficient mechanism for the formation of a mixing layer leading to solar wind plasma entering the magnetosphere. Furthermore, the vortices drag in their flow the magnetic field component parallel to the solar wind direction. As a consequence, the magnetic field lines are increasingly stretched inside the vortices until they reconnect. Besides transforming plasma kinetic energy into accelerated particle energy, heating, magnetic reconnection also affects the transport properties of the plasma and vortex-induced reconnection [23, 30], has been considered to be an efficient mechanism of vortex disruption and to allow eventually solar wind plasma to enter the magnetosphere [31, 25, 26].

On the other hand, pairing of the vortices generated by the Kelvin-Helmholtz instability is a well know phenomenon in two-dimensional hydrodynamics [32, 33]. In fact the role of the magnetic field on vortex dynamics has been studied essentially in the limit of only one vortex, the largest one contained in the simulation box. It has been shown that, even if the magnetic field is weak and unable to prevent the formation of the Kelvin-Helmholtz vortex, nevertheless the vortex-induced reconnection process eventually leads to vortex disruption [25, 26, 34].

On the contrary, three recent papers have investigated the development of secondary instabilities during the vortex pairing process (a vortex-induced Rayleigh-Taylor instability in Ref. [35] and vortex-induced magnetic reconnection in Refs. [36, 37]). In particular it has been shown that completely different magnetic structures are produced depending on how fast these secondary instabilities develop on the time scale set by the pairing process.

2. Competing instabilities

Fluids and plasmas in nature do not usually manifest themselves in quiescent stationary or quasistationary states (what we generally call “equilibria”) but exhibit a rich dynamical behaviour consisting of linear and nonlinear waves and instabilities, coherent nonlinear structures such as vortices and solitary perturbations, or fully developed turbulence.

In the following we will focus our attention not so much on the single instability mechanism and the single instability growth and saturation, but mainly on the competition between a restricted number of instabilities of the system, and on how this competition may become experimentally observable in specific plasma regimes of interest. Different instabilities can compete either because they are present from the start, as they can feed on the same energy source present from the start in the equilibrium configuration, or because they arise as secondary instabilities that feed on an energy source that was not present initially in the equilibrium configuration but that has been made available by the development of the primary instability.

The Kelvin-Helmholtz, the Rayleigh-Taylor and the magnetic reconnection instabilities are the main actors on the stage of the nonlinear dynamics of a magnetized plasma, as they can be driven directly or indirectly, i.e., in the form of secondary instabilities, by inhomogeneities in the plasma velocity, in the plasma density (or pressure) and in the plasma currents. The complex interaction between these instabilities is controlled by the time scales of the different processes at play, which involve both large spatial scales from which the initial drive of the instabilities originates, and small spatial scales where e.g., magnetic field line reconnection can occur. The timing between the two instabilities will determine the structure of the final configuration that the system can reach. The qualitative differences (not simply quantitative differences) between these possible final states are evident and can in principle be used as a diagnostic tool in order to determine experimentally how fast reconnection evolves in the different plasma regimes on the clock set by the evolution of the primary instability.

In this article we will investigate the interplay and the competition between a Kelvin-Helmholtz primary instability, with its nonlinear evolution characterized by the vortex pairing process, and the onset of secondary instabilities, such as magnetic reconnection in the case of a frozen magnetic field with field lines stretched by the differential plasma motion generated by
the Kelvin-Helmholtz instability. We will also briefly consider the effect of a secondary Rayleigh Taylor instability driven by the centrifugal acceleration in vortices in a plasma with a strong density inhomogeneity.

3. Configurations with a velocity shear and a density gradient
First we report some recent results [35] on the interplay between the Kelvin-Helmholtz instability and a secondary Rayleigh-Taylor instability driven by the acceleration inside the rotating vortices in the presence of a plasma density gradient. Such a configuration is of interest for the case of the interaction of the solar wind with the Earth magnetosphere in regions where magnetic reconnection is not expected to occur.

Two-dimensional simulations [35] of the Kelvin-Helmholtz instability show that in an inhomogeneous compressible plasma with a density gradient (in a transverse magnetic field configuration) the vortex pairing process and the Rayleigh-Taylor secondary instability compete during the non-linear evolution of the vortices. Two different regimes have been shown to exist depending on the value of the density jump across the velocity shear layer. These regimes have different physical signatures that can be crucial for the interpretation of satellite data of the interaction between the solar wind and the magnetospheric plasma.

As mentioned in the Introduction, the Kelvin-Helmholtz instability has been shown [28] to play a crucial role in the interaction between the solar wind and the Earth’s magnetosphere and to provide a mechanism by which the solar wind can enter the Earth’s magnetosphere. In fact magnetic reconnection is believed to dominate the transport properties at the low latitude magnetopause when the field in the solar wind and the geomagnetic field are antiparallel (southward solar wind magnetic field). The reasoning goes that if magnetic reconnection were the only mixing mechanism in the magnetotail, the mixing between the solar wind and the magnetospheric plasma should not occur during northward magnetic field periods. Actually, an increase of the plasma content in the outer magnetosphere during northward magnetic field periods is not only observed but is even larger than during southward configurations [38, 39, 28]. For these reasons, the Kelvin-Helmholtz instability has been invoked as a possible mechanism in order to account for the increase of the plasma transport. In particular, the Kelvin-Helmholtz instability can grow along the flank magnetopause at low latitude, where a velocity shear exists and where the nearly perpendicular magnetic field does not inhibit the development of the instability [40, 41, 27]. The Kelvin-Helmholtz instability thus provides an efficient mechanism for the formation of a mixing layer and for the entry of solar plasma into the magnetosphere, explaining the efficient transport during northward solar wind periods. Several observations support this explanation and show that the physical quantities observed along the flank magnetopause at low latitude are compatible with a Kelvin-Helmholtz vortex [28, 42, 23].

The process of vortex pairing mentioned before is a basic two-dimensional hydrodynamic inverse cascade phenomenon [32, 33] and can be expected to be an efficient process in the nearly two-dimensional external region of the magnetopause at low latitude [29, 23] and is believed to be the major process causing the increase in the thickness of the mixing layer in the downstream region of the magnetotail. However, the density inhomogeneity in the layer between the solar wind and the magnetosphere strongly modifies the non-linear evolution of the Kelvin-Helmholtz instability as the Kelvin-Helmholtz vortices cause the onset of a secondary instability which quickly leads to the onset of turbulence [43, 44] in the system. In fact the centrifugal acceleration of the rotating Kelvin-Helmholtz vortex acts as an “effective” gravity force on the plasma. If the density variation is large enough, the Rayleigh-Taylor instability can grow effectively along the vortex arms. How quickly the vortex becomes turbulent is crucial since the turbulence caused by the onset of the Rayleigh-Taylor secondary instability may destroy the structure of the vortices before they coalesce and may thus be the major cause of the increase in the width of the layer with increasing velocity and density inhomogeneity.
Rolled-up vortices, generated by the fast growing mode of the Kelvin-Helmholtz spectrum and entering in the non-linear stage, could then evolve following an inverse cascade process, or by developing a secondary Rayleigh-Taylor instability. In order to separate the effect of the onset of a secondary vortex-induced reconnection process which will be discussed in the next section, here we consider the initial magnetic field to be perpendicular to the plane where the Kelvin-Helmholtz instability develops and to have no inversion points.

In Ref. [35] it has been shown numerically (see first part of the Appendix) that for a relatively moderate initial density jump corresponding in dimensionless units to $\Delta n = 0.5$, the evolution of the Kelvin-Helmholtz vortices is not disrupted by the onset of a secondary Rayleigh-Taylor instability. In Figs.1,2 the shaded isocontours of the plasma density in the $(x, y)$ plane for an initial density jump $\Delta n = 0.5$ at $t = 370$ and at $t = 425$ show the formation and the evolution of these vortices. The two vortices start to interact following an inverse cascade and eventually merge generating a single vortex.

On the contrary in the case of a large initial density jump, $\Delta n = 0.8$, the evolution of the system is strongly affected by the development of secondary Rayleigh-Taylor instabilities inside the vortex arms. After the generation of the two Kelvin-Helmholtz vortices, Figs. 3,4, the Rayleigh-Taylor instability starts to develop inside the arms of the vortices, leading to the formation of a turbulent layer along the $y$-direction with typical transverse width of the order of the vortex size. The vortex pairing interaction is depressed by the onset of the secondary instability.

![Figure 1](image1.png) ![Figure 2](image2.png)

**Figure 1.** Plasma density isocontours for $\Delta n = 0.5$ at $t = 370$

**Figure 2.** Plasma density isocontours for $\Delta n = 0.5$ at $t = 425$

![Figure 3](image3.png) ![Figure 4](image4.png)

**Figure 3.** Plasma density isocontours for $\Delta n = 0.8$ at $t = 350$

**Figure 4.** Plasma density isocontours for $\Delta n = 0.8$ at $t = 425$

In order to estimate the growth time of this secondary instability, we may consider each of the two vortices generated by the Kelvin-Helmholtz instability separately and assume such a structure to be stationary in the time interval $300 \leq t \leq 350$. During this period, the vortex propagates along the $y$-direction with a constant phase velocity and nearly constant amplitude.
We may model the vortex at \( t = 300 \) as an ’‘equilibrium” configuration and take the values \( n_1, u_1 \) and \( n_2, u_2 \) (as defined in the Appendix) inside two nearby vortex arms connected to the more and to the less dense parts of the plasma respectively, as the density and velocity values of two superposed inhomogeneous fluid plasmas in a slab geometry. In this model, the two plasma slabs are subjected to an effective gravity which corresponds to the centripetal acceleration arising from the arms curvature. Taking into account the profiles of the velocity shear and of the density of the vortex, we find that the estimate of the growth rate of the Rayleigh-Taylor instability is in agreement with that observed in the numerical simulations.

The competition between the vortex pairing process and the development of the Rayleigh-Taylor instability has important consequences from an observational point of view and can affect the transport properties of the system, see Ref. [35]. In the pairing case the density profile along the wind direction (along \( y \)) is characterized by well defined structures consisting of the well known step-like configuration that is directly related to the two vortex arms connected to the more and to the less dense parts of the plasma, and of a filament-like configuration that is related to the more complex central region of the vortex. This profile exhibits a well-defined periodicity, given by the wave length of the vortex, and is the signature of a rolled-up vortex. It corresponds either to the fast growing mode or to its sub-harmonics generated by the inverse cascade.

On the other hand, in the case where the secondary instability develops, the density profile along \( y \) exhibits a sequence of alternating high and low density filaments with no well defined wave length. This fact is related to the transition of the system to a turbulent state with the formation of a mixing layer via the development of smaller and smaller structures.

4. Configurations with a velocity shear and an in-plane magnetic field

In a magnetized plasma streaming with a nonuniform velocity, the Kelvin-Helmholtz instability plays a major role not only by mixing the plasma but also by stretching the magnetic field lines leading to the formation of layers with a sheared magnetic field where magnetic field line reconnection can take place. We refer again to the formation of a mixing layer between the Earth’s magnetosphere and the solar wind at low latitudes during northward periods when the solar wind and the geomagnetic magnetic fields are parallel. As already discussed, velocity shear, in the presence of a magnetic field nearly perpendicular to the plane defined by the velocity field and its inhomogeneity directions, makes the Kelvin-Helmholtz instability grow along the flank magnetosphere.

If the Alfvén velocity associated to the in-plane magnetic field is sufficiently weak with respect to the fluid velocity jump, the Kelvin-Helmholtz instability forms fully rolled-up vortices which advect the magnetic field lines into a complex magnetic configuration. This advection causes the in-plane magnetic field component to develop inversion points where magnetic reconnection can take place. Since the plasma dynamics is essentially driven by the vortex motion, these reconnection events are usually denoted as vortex-induced reconnection. Although magnetic reconnection occurs only locally, this process changes the global topology of magnetic field, which is a necessary condition for plasma mixing, and thus the evolution of the vortices themselves.

Here we report the results of recent numerical investigations [36, 37] on the development of magnetic reconnection during the vortex pairing process and show that completely different magnetic structures are produced depending on how fast the reconnection process develops on the time scale set by the pairing process.

We consider a configuration (see second part of the Appendix) with a value of the plasma \( \beta \) parameter (defined as the ratio of the plasma pressure over the total magnetic field pressure) of order unity and show that in this regime the Hall term in Ohm’s law, which arises from the decoupling of electrons and ions inside the current layers, allows magnetic reconnection to occur on time scales fast enough to compete with the pairing process. It is important to stress that in the numerical simulations in Refs. [36, 37] the conditions for magnetic reconnection are naturally
provided, in an initially uniform in-plane magnetic field, by the motion of the Kelvin-Helmholtz vortices that grow and pair in the initially imposed shear velocity field.

We find that if the Hall term is removed from Ohm’s law, the development of reconnection, and thus eventually of the Kelvin-Helmholtz vortices, is qualitatively, not only quantitatively, different. This result provides a clear cut example of the feedback between large and small scale physics, as the necessary conditions for reconnection to occur are produced by the motion of the large scale vortices, but the specific physical processes that make reconnection act faster or slower determine eventually the evolution of the entire system and the final magnetic field structure.

In Figs. 5-8 we show the magnetic field lines and a plasma passive tracer, advected by the velocity field, which is used in order to label the plasma domains initially on the right and on the left of the velocity null line.

In Fig. 5 we see the two vortices generated by the Kelvin-Helmholtz instability, corresponding to the fast growing mode wave number \( m = 2 \). As soon as the system enters the non-linear phase of the Kelvin-Helmholtz instability, the vortices start to pair following an inverse cascade process typical of two dimensional fluid systems. In Fig. 6 we see that the black and the gray domains are well separated by a ribbon (white in the figure) of nearly parallel, compressed magnetic lines. This ribbon is rolled-up by the rotation of the two vortices, and forms inside the folds between the vortices two current layers corresponding to two local magnetic inversion lines. We also see the formation of a first couple of \( X \)-points (one per vortex) in this region at \( x_1 = 44, y_1 = 65 \) and at \( x_2 = 45, y_2 = 35 \), respectively. This is the first reconnection event observed in our simulation. At \( t = 437 \) we show in Fig. 7 the formation of a second pair of \( X \)-points (one per vortex) in the same inversion region \( (x_3 = 44, y_3 = 50 \text{ and } x_4 = 45, y_4 = 47) \). Magnetic reconnection develops at these \( X \)-points and forms magnetic islands with typical size \( \sim d_L \), the maximum value compatible with the dimension of the current sheet. At the same time, the field line ribbon between the second pair of \( X \)-points shrinks and finally opens up. A new ribbon of field lines appears at \( t = 460 \), Fig. 8. This new ribbon no longer separates the gray and the black plasma regions. Indeed, during this process, significant portions of the gray plasma have been engulfed in the form of "blobs" into the black plasma region and viceversa. The inflow plasma velocity at the second pair of \( X \)-points is approximately 0.1 times the value of the local Alfvén velocity \( U_A \) in the \( x-y \) plane, in agreement with the values of the inflow velocity expected in the case of fast magnetic reconnection. Note that in the time interval given by a few growth times (a few times \( \gamma^{-1} \)) of the reconnection instability, the two vortices can only rotate by a few degrees so that the plasma displacement and the current rearrangement caused by the vortex rolling up are not sufficient to interfere with the development of the reconnection process.

In Ref. [37] it is shown that the ion decoupling region extends across the \( X \)-points over few \( d_L \) lengths. Inside this region the magnetic field is essentially frozen in the electron motion but the magnetohydrodynamic frozen-in law is not satisfied as the Hall term \( \mathbf{J} \times \mathbf{B} \) becomes as large as the leading terms in the generalized Ohm’s law. Inside a thinner region of width \( d_e \) the electrons are also decoupled from the magnetic field and magnetic reconnection can take place. Inside the thinner electron region the electrons are also decoupled from the magnetic field and magnetic reconnection can take place.

The role of the Hall term has also been demonstrated in Ref. [37] by running again the same simulation parameters simply omitting the Hall term in the generalized Ohm’s law. Although the large scale motion of the vortices is still able to generate current sheets of comparable intensity and width, the process of magnetic reconnection is slower. In particular it does not succeed in forming the second pair of \( X \)-points quickly enough. The two vortices continue to roll-up while pairing and develop into a different magnetic pattern where magnetic islands are eventually generated all over the vortices leading to the disruption of the vortices. The rolling up and pairing of the vortices develops on a time scale comparable with the reconnection time.
Figures 5-8 show in-plane magnetic configuration at different times:

- **Figure 5.** In-plane magnetic configuration at $t = 350$
- **Figure 6.** In-plane magnetic configuration at $t = 427$
- **Figure 7.** In-plane magnetic configuration at $t = 437$
- **Figure 8.** In-plane magnetic configuration at $t = 460$
and affects its evolution. This competition between the development of the large scale magnetic configuration and the evolution and the reconnection instability determine the development of the entire system. If magnetic reconnection is not fast enough, the rolling up of the vortices destroys the favourable conditions for the reconnection instability to grow.

5. Conclusions
In this article we discussed how the competition between primary and secondary instabilities in a plasma can lead to qualitatively different physical states. These differences can be observed experimentally. Thus the outcome of this competition can give us important pieces of information on the time development of the instabilities as we can use one as a clock in order to measure the time development of the other.

We have considered a two dimensional plasma configuration with an initial large scale velocity shear and we have studied the interplay between the nonlinear development of the Kelvin-Helmholtz instability and the Rayleigh-Taylor instability driven by the centrifugal acceleration within the Kelvin-Helmholtz vortices in the presence of a density gradient. We have then studied the interplay between the nonlinear development of the Kelvin-Helmholtz instability and a magnetic reconnection instability driven by the current layers within the Kelvin-Helmholtz vortices in the presence of an initially uniform in-plane magnetic field. Actually in a real configuration both secondary instabilities should be considered as acting together.

In the case of the secondary magnetic reconnection instability we have considered a configuration with a value of the plasma $\beta$ parameter of order unity and have shown that in this regime the Hall term in Ohm’s law, which arises from the decoupling of electrons and ions inside the current layers, allows magnetic reconnection to occur on time scales fast enough to compete with the pairing process of the Kelvin-Helmholtz vortices.

In the literature, fast reconnection has been studied in a pre-imposed magnetic configuration consisting of a small region around a magnetic X-point, with a ”forced” plasma inflow from the boundary towards the reconnection region. In the simulations presented in Refs. [36, 37] and reviewed here the conditions or magnetic reconnection are naturally provided, in an initially uniform in-plane magnetic field, by the motion of the Kelvin-Helmholtz vortices that grow and pair in the initially imposed shear velocity field. We have found that if the Hall term is removed from Ohm’s law, the development of reconnection, and thus eventually of the Kelvin-Helmholtz vortices, is qualitatively, not only quantitatively, different. This result provides a clear cut example of the feedback between large and small scale physics, as the necessary conditions for reconnection to occur are produced by the motion of the large scale vortices, but the specific physical processes that make reconnection act faster or slower determine eventually the evolution of the entire system and the final magnetic field structure.

Appendix
Simulation and plasma parameters for a configuration with a velocity shear and a density gradient
We consider a two dimensional description of the system, with the inhomogeneity direction along $x$, and the $y$-axis along the solar wind. This choice is justified since the evolution of Kelvin-Helmholtz instability is only weakly affected by slow equilibrium variation along the $z$-direction [41, 27]. We adopt a quasineutral plasma model described by the following set of single-fluid equations which we write in dimensionless conservative form as

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{U}) = 0,$$  \hspace{1cm} (1)
with \( n \) the plasma density and \( U \) the fluid velocity.

\[
\frac{\partial (nU)}{\partial t} + \nabla \cdot \left[ nUU + \frac{PT}{\mu_0} \nabla I - \frac{BB}{\sigma} \right] = 0,
\]

(2)

with \( P_T = P + B^2/2 \), which is constant at \( t = 0 \), and the isothermal closure

\[
\frac{\partial P}{\partial t} + \nabla \cdot (PU) = 0.
\]

(3)

The characteristic dimensional quantities are the mass density, the Alfvén velocity and the ion skin depth. The electric field is calculated by means of Ohm’s law

\[
E = -U \times B,
\]

(4)

where electron inertia and pressure terms are neglected. The equilibrium magnetic field at \( t = 0 \) is taken of the form \( B_{eq}(x) = B_{eq}(x)e_z \). In this two dimensional transverse configuration \( B(x, y, t) \) follows a pure magnetohydrodynamic evolution also if the Hall term is included in Ohm’s law. The magnetic field contributes only to determining the degree of compressibility of the plasma in the perpendicular plane which otherwise behaves hydrodynamically. For the low frequency range of interest the displacement current is not included.

The above equations are integrated by means of a numerical code. In this code, numerical stability is achieved by means of filters [45].

We consider an initial large-scale, sheared velocity field given by

\[
U_{eq} = \frac{U_0}{2} \tanh \left( \frac{x - L_x/2}{L_x} \right) \hat{y}
\]

(5)

and an equilibrium density of the form

\[
n_{eq} = \frac{1}{2} \left[ (2 - \Delta n) + \Delta n \tanh \left( \frac{x - L_x/2}{L_x} \right) \right]
\]

(6)

We take \( L_x = L_n = 3.0 \) and the box-length in the \( x \) direction \( L_x = 90 \). We choose the box length \( L_y = 24\pi \) in the periodic \( y \) direction, in order to have well separated linear growth rates for the modes \( m = 1, 2, 3 \), where \( m = 2 \) corresponds to the fast growing mode. The values of the two dimensionless parameters, the sound and Alfvén Mach numbers, are set as \( M_s = U_0/C_s = 1.0 \), \( M_A = U_0/U_A = 1.0 \), with \( U_A = 1.0 \) the value of the Alfvén velocity at \( x = L_x \).

**Simulation and plasma parameters for a configuration with a velocity shear and an in-plane magnetic field**

We consider again a two dimensional description of the plasma configuration and adopt a two-fluid, quasineutral plasma model which is equivalent to a magnetohydrodynamic description with a generalized Ohm’s law that includes the electron inertia and the Hall terms. In this model the electric field \( E \) is calculated by means of the following generalized Ohm’s law [46] \((u_e \), electron velocity, \( u_i \) ion velocity, \( j = ne(u_i - u_e) \))

\[
\left( 1 - d_e^2 \nabla^2 \right) E = -u_i \times B + \frac{1}{n} \hat{j} \times B - \frac{1}{n} \nabla P_e
\]

(7)

where normalized quantities are used. We consider the same initial large-scale, sheared velocity field as given by Eq.(5) but. since we are primarily interested in the reconnection process, we consider a homogeneous density field in order to eliminate other secondary fluid instabilities.

The equilibrium magnetic field at \( t = 0 \) is homogeneous and given by

\[
B_{eq}(x, y) = B_{y, eq} e_y + B_{z, eq} e_z.
\]

(8)
We take $L_u = 3.0$ and the box-length in the $x$ direction $L_x = 90$. The box length in the periodic $y$-direction is $L_y = 30\pi$ in order to have well separated linear growth rates for the modes $m = 1, 2, 3$, where $m = 2$ corresponds to the fast growing mode of the Kelvin-Helmholtz instability. We take $d^2 = m_c/m_i = 1/64$.

The values of the dimensionless sound and Alfvén Mach numbers are set as $M_s = U_0/C_s = 1.0$, $M_{A,\perp} = U_0/U_{A,\perp} = 1.0$, $M_{A,\parallel} = U_0/U_{A,\parallel} = 20.0$, with $U_0 = 1.0$ and $U_{A,\perp}, U_{A,\parallel}$ the $z$ and $y$ component of the equilibrium Alfvén velocity, respectively. This choice allows the Kelvin-Helmholtz instability to develop into highly rolled-up vortices.

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