

## Fast magnetic reconnection in collisionless plasmas with velocity shear

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### Abstract

In plasma configurations, such as those produced by the onset of the Kelvin-Helmholtz instability in a plasma with a velocity shear, qualitatively different magnetic structures are produced depending on how fast the reconnection process develops and competes with the pairing process of the vortices produced by the Kelvin-Helmholtz instability.

In a magnetized plasma streaming with a nonuniform velocity, the Kelvin-Helmholtz (K-H) 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 K-H 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 K-H 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 K-H instability is a well known phenomenon in 2-D 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.

We consider a configuration 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. In our simulations the conditions for magnetic reconnection are naturally provided, in an initially uniform in-plane magnetic field, by the motion of the K-H 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 K-H 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 large scale vortices motion, 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.

We consider a 2D description of the system, with the inhomogeneity direction along  $x$ , the periodic direction along  $y$ , and  $z$  an ignorable coordinate. We adopt a two-fluid, quasineutral plasma model. and the electric field  $\mathbf{E}$  is calculated by means of the following generalized Ohm's law  $(1 - d_e^2 \nabla^2) \mathbf{E} = -\mathbf{u}_e \times \mathbf{B} - d_e^2 \{ \mathbf{u}_i \times \mathbf{B} + (1/n) \nabla \cdot [n(\mathbf{u}_i \mathbf{u}_i - \mathbf{u}_e \mathbf{u}_e)] \}$  where the term  $\nabla P_e/n$  has been omitted since, for a polytropic equation of state, it does not contribute to  $\nabla \times \mathbf{E}$ . We consider an initial large-scale, sheared velocity field given by  $\mathbf{U}_{eq} = (U_0/2) \tanh[(x - L_x/2)/L_u] \hat{\mathbf{y}}$ . Since we are primary interested in the reconnection process, we consider a homogeneous density field in order to eliminate other secondary fluid instabilities[1]. The equilibrium magnetic field at  $t = 0$  is homogeneous and given by  $\mathbf{B}_{eq}(x, y) = B_{y,eq} \mathbf{e}_y + B_{z,eq} \mathbf{e}_z$ . 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 (FGM) of the K-H instability. 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 K-H instability to develop into highly rolled-up vortices. We take  $d_e^2 = m_e/m_i = 1/64$ .

In Fig.1 we show the nearly *frozen-in* 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 the first frame (upper-left), we see the two

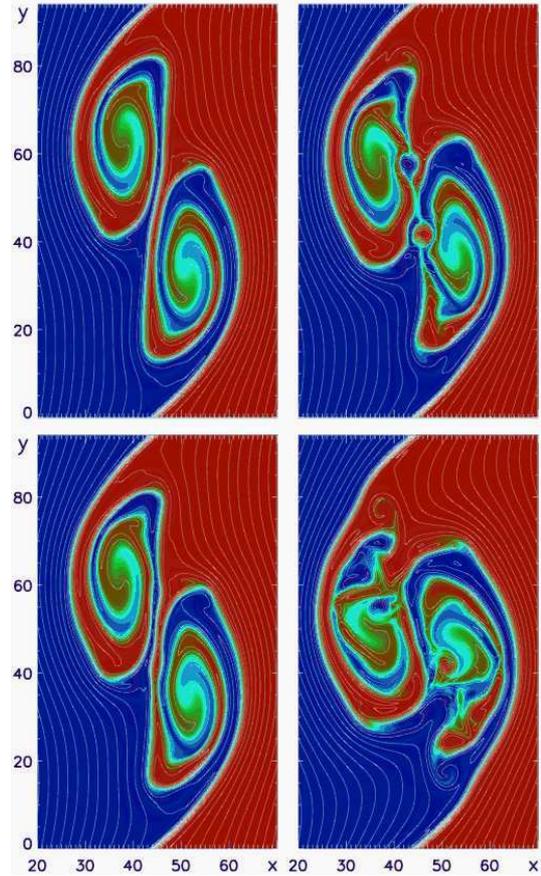


Figure 1: Plasma passive tracer and magnetic field lines in the  $(x, y)$  plane at  $t = 426, 435$  (left), and  $t = 460, 480$  (right).

vortices generated by the K-H instability, corresponding to the FGM wave number  $m = 2$ . As soon as the system enters in the non-linear phase of the K-H instability, the vortices start to pair following an inverse cascade process typical of 2D fluid systems. The good correlation between the plasma and the magnetic structures indicates that the magnetic field is still advected by the fluid velocity. In the first frame we see that the blue and the red domain 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 for 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  $t = 440$  we show in the second frame (left-bottom) the formation of a second pair of  $X$ -points (one for vortex) in the same inversion region ( $x_3 = 44, y_3 = 50$  and  $x_4 = 45, y_4 = 47$ ). Magnetic reconnection develops at these  $X$ -points and forms magnetic islands with typical size  $\sim d_i$ , 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  $t = 450$ , right top frame. This new ribbon no longer separates the red and the blue plasma regions. Indeed, during this process, significant portions of the red plasma have been engulfed in the form of "blobs" into the blue plasma region and viceversa (right-bottom).

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. Then, the growth rate  $\gamma$  of magnetic reconnection is inferred to be  $\gamma \sim 0.1U_a/L \sim 0.15$ , where  $L$  is the shear-length of the in-plane magnetic field at the  $X$ -points. Note that in the time interval given by a few growth times (a few times  $\gamma^{-1}$ ) of the reconnection insta-

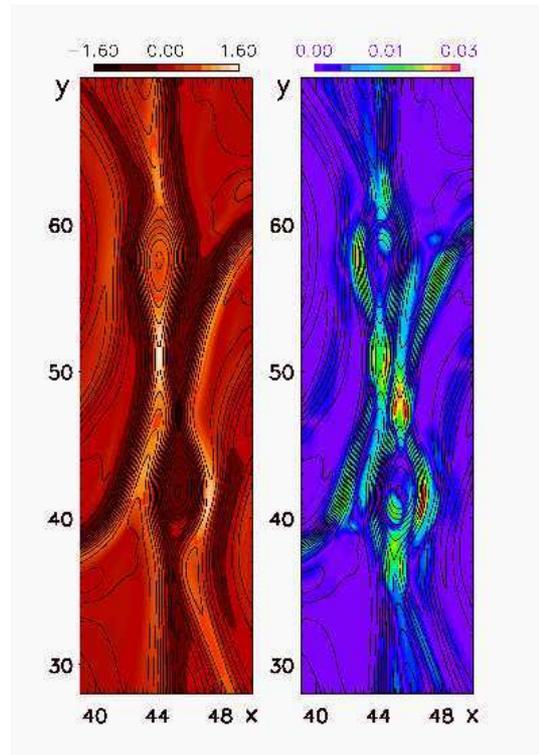


Figure 2: Left frame: shaded isocontours of the perpendicular current density and magnetic field lines in the region between the two pairing vortices at  $t = 440$ . Right frame: Ion decoupling region and magnetic field lines in the same region at  $t = 440$ .

bility, 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 Fig.2, right frame, we show a wide ion decoupling region. This region extends across the  $X$ -points over few  $d_i$  lengths. Inside the ion decoupling region, of width roughly equal to  $1.5d_i$ , the magnetic field is essentially frozen in the electron motion but the MHD frozen-in law is not satisfied and the two terms  $\mathbf{U} \times \mathbf{B}$  and  $\mathbf{J} \times \mathbf{B}$  have approximately the same absolute value. Inside the thinner electron region also the electrons are decoupled from the magnetic field and magnetic reconnection can take place.

The crucial role of Hall term has also been demonstrated by running again the same simulation parameters simply omitting the Hall term in the generalized Ohm 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 in Fig.1 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 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 favorable conditions for the reconnection instability to grow.

## References

- [1] M. Faganello *et al.*, Phys. Rev. Lett. **100**, 015001 (2008)