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Three-Dimensional Simulations of Magnetic Reconnection with or Without Velocity Shears

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Abstract The properties of spontaneous reconnection of a current sheet analyzed via direct three-dimensional simulations are presented. In particular the non-linear dynamics of resistive instabilities has been studied in absence or in presence of velocity shears. It is shown that full three-dimensional simulations allow the inclusion of a rich variety of (ideal) secondary instabilities which, depending on the initial equilibrium magnetic field configuration, determine the final fate of the system in the fully non linear regime. In particular in presence of a guide-field the dynamic is similar to what observed in two-dimensional simulations with energy driven toward both smaller and larger scales and energy spectra anisotropy. For different magnetic field configurations, the final state is characterized by the disruption of the coalesced structure created during the resistive phase and the system is characterized by a more chaotic state. A discussion on the importance of high-order numerical techniques in numerical simulations of magnetic reconnection is also present.

Keywords Magnetic reconnection · Plasma instabilities · Sun · Solar wind

1 Introduction

Magnetic reconnection is a fundamental process which drives many observed phenomena occurring in astrophysical, space and laboratory plasmas. In particular within the heliosphere bursty releases of mass and energy, such as solar flares and coronal mass ejections are related to a sudden conversion of magnetic energy into kinetic energy, heating, and particle acceleration via fast magnetic reconnection. Smaller reconnection events such as ‘nanoflares’ can also be a viable mechanism to account for the one million kelvin solar

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corona (Parker 1983). Reconnection has been observed in the solar wind (Gosling and Szabo 2008), in the magnetosphere (Sonnerup et al. 1981; Paschmann 2008) and in the magnetosheath (Retinò et al. 2007; Sundkvist et al. 2007). Numerical simulations have shown that reconnection is a fundamental ingredient in fully developed incompressible MHD turbulence (Servidio et al. 2009, 2010).

Fast, inhomogeneous plasma flows are ubiquitous throughout the heliosphere, e.g as the result of acceleration processes in the solar corona and/or from magnetic reconnection itself. The basic solar wind structure at solar minimum consists of high speed streams, originating from the polar coronal hole, and a much slower stream (the slow wind) surrounding the streamer belt above the solar magnetic equator (McComas et al. 1998). Strong ballerina-skirt undulations of the heliospheric current-sheet are associated with the development of compressive structures due to the overlap of fast and slow streams, forming co-rotating interaction regions eventually developing shocks far away from the Sun (Gosling 1996). In the far region of the heliosphere, the current sheet must be carried across the termination shock: the combined interaction of magnetic field and sheared flows there determines the structure of the heliosheath, as suggested by numerical simulations (Opher et al. 2003, 2004).

The low to moderate values of the plasma beta implies that most flows and sheared streams observed throughout the heliosphere are supersonic: as an example the differential velocity between fast and slow streams in the solar wind exceeds both the Alfvèn speed and the sound speed. Moreover the flows resulting from acceleration processes are supersonic in the low beta solar corona.

The presence of current sheets embedded in sheared flows are subjected to both resistive tearing (Furth et al. 1963) and Kelvin-Helmholtz (KH) instabilities. The combined effects of those instabilities may help to understand much of the observed phenomenologies seen in the solar atmosphere and wind: from the acceleration of the slow solar wind (Einaudi et al. 1999) and the formation and acceleration of plasmoids above the helmet streamer (Rappazzo et al. 2005) as observed in coronograph data (Sheeley et al. 1997; Wang et al. 1998), to spicules and macrospicules observed in the chromosphere and transition region as well as coronal plumes and pressure-balanced structures in the solar wind (DeForest et al. 2001; McComas et al. 1995).

2 The 2D Evolution of Tearing with and Without Sheared Flows

The basic instability of a current sheet is the tearing instability whose linear properties were analytically studied by Furth et al. (1963) and numerically investigated by Wesson (1966) and Steinolfson and van Hoven (1983). The non-linear evolution of the instability is characterized both by an energy transfer to high wave numbers and by an inverse cascade which in the physical space corresponds to the formation of magnetic islands with larger and larger size (see Fig. 1). The physical mechanism behind the inverse cascade is different here with respect the coalescence instability (Finn and Kaw 1977; Pritchett and Wu 1979; Biskamp and Welter 1980; Bondeson 1983a; Bhattacharjee et al. 1983). In the coalescence instability the process is driven by the attraction of current filaments whose maxima are located in correspondence of the O-points, while in the tearing instability the current maxima are located at the X-point and the coalescence is driven by the stretching of the most intense current sheet (Hayashi 1981; Malara et al. 1991, 1992). For large systems, i.e. for systems where the current sheet length connecting two plasmoids is large enough, beyond a critical value of the Lundquist number, a secondary two-dimensional instability occurs rapidly (faster than ideal time-scales). Such instability is characterized by the formation of a large

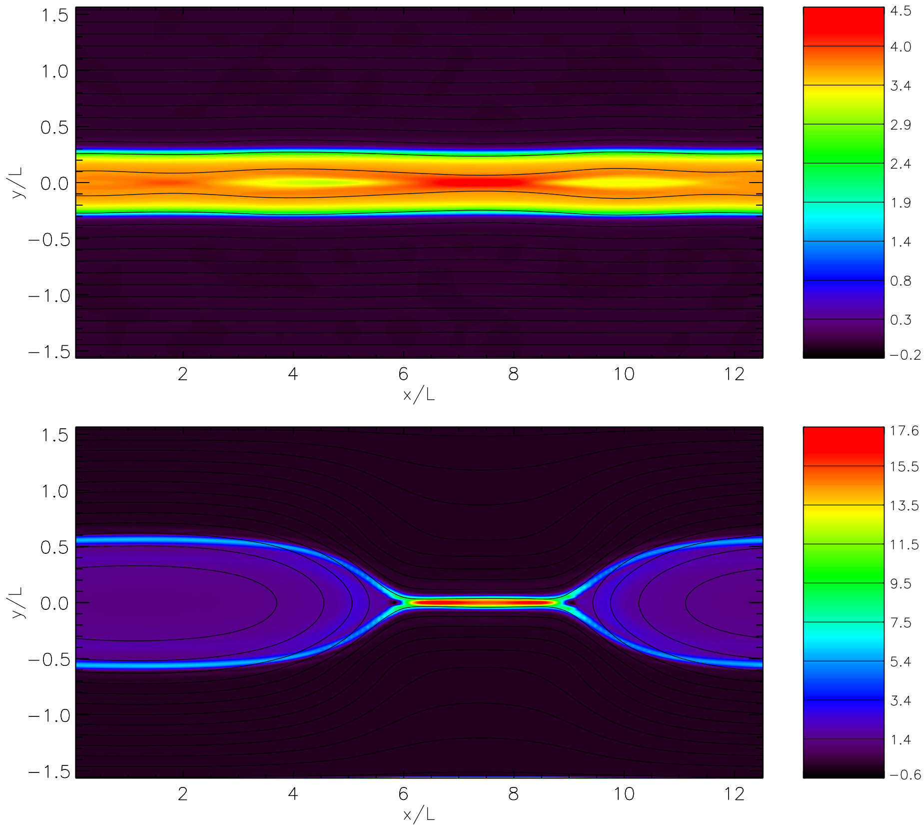

Fig. 1 An example of the development of the tearing instability in a current sheet. In the *top panel*, the structure of the current density intensity (color) and magnetic field lines at the early stage of the instability are shown. Two X-points are reconnecting at about $x = 2$ and $x = 7$. The most intense of them dominates the late evolution of the instability creating an intense final single current sheet (*bottom panel*)

number of plasmoid chains and the reconnection rate inside the current sheet is observed to be weakly dependent on the magnetic diffusivity (Lapenta 2008; Skender and Lapenta 2010; Loureiro et al. 2007; Samtaney et al. 2009; Cassak et al. 2009; Bhattacharjee et al. 2009; Huang and Bhattacharjee 2010). More recently however, Ng and Ragunathan (2011) have shown that secondary island formation at high Lundquist numbers (up to 2×10^5) is prevented by performing high resolution and high order numerical simulations (Ng et al. 2008). If a small amount of noise is added externally, secondary magnetic islands are created and a weakly dependence on the Lundquist number of the magnetic reconnection rate is observed, suggesting that such fast process is intimately related to MHD turbulence (e.g. Lazarian and Vishniac 1999).

Current sheets embedded in a sheared flow can be driven primarily by a resistive-like instability or by a KH-like instability according to the ratio between the current-sheet and the shared flow thickness and on the Alfvènic Mach number against the differential velocity between the shears (Dahlburg et al. 1997, 1998). In the case where the thickness of the current sheet is much smaller than the shear layer, for a differential velocity exceeding not too much the Alfvèn Mach number (a paradigm for the acceleration region of the slow solar wind) the resistive mode dominates. The destabilization of the velocity shear then produces the acceleration of the magnetic islands. The non-linear phase of the instability produces an enlargement of the shear with the reduction of the differential velocity and the mixing of the two flows (Einaudi et al. 1999, 2000). These processes has been thought to explain the slow solar wind origin (Einaudi et al. 2000), whereas the plasma density enhancement observed to be ejected from the top of the helmet streamer (Sheeley et al. 1997; Wang et al. 1998) has been associated with the tearing instability in a velocity shear (Einaudi et al. 2001). The linear and non-linear phase of the resistive instability in this context has been studied considering the effect of the expansion and of the melon seed force (Rappazzo et al. 2005) as well as including the effect of the Parker's spiral (Bettarini et al. 2006) (Fig. 2). In another astrophysical contest the interaction with a current sheet embedded in a wake flow has been also used as a model of the formation of isolated non thermal filaments in the galactic center (Shore and Larosa 1999; Dahlburg et al. 2002).

3 Handling Reconnection with Simulations. The Importance of the Numerical Strategy

The study of resistive instabilities in the theoretical framework of compressible magneto-fluids requires numerical techniques that, on the one hand, are able to properly capture both resistive instabilities and reconnection processes and, on the other hand, are able to handle strong discontinuities which arise naturally in high Mach number flows. To understand resistive instabilities and magnetic reconnection requires high-order, spectral-like techniques where the coefficients can be explicitly controlled and reconnection rates scale explicitly as some power of the dissipative coefficients. In coronal and heliospheric plasma magnetic reconnection is often controlled by kinetic effects, such as the Hall term. The dispersion and the wave-modes carried by the plasma, which are important in reducing the dependence of the growth rate on the Reynolds number (Birn et al. 2001), must be properly resolved in numerical simulations using high-order spectral-like methods. Moreover, the lack of control over the numerical diffusivity leads to lost intermittent features at smallest scales, e.g. the acceleration region of the slow solar wind above the helmet streamer: in global 3D MHD simulations this region is a dead zone for the wind and the flow is laminar while numerical simulations using pseudo-spectral techniques are able to capture the formation of plasmoids driven by resistive instabilities (Rappazzo et al. 2005; Bettarini et al. 2006). On the other hand, the shocks which develop in high-Mach number flow require the use of numerical techniques, such as upwind methods with Essentially Non Oscillatory (ENO) interpolation polynomials, explicitly designed to treat discontinuities.

The ECHO (Eulerian Conservative High Order) code reconciles shock-capturing properties with high-order spectral-like differentiation schemes. It is based on the Upwind Constrained Transport (UCT) methodology (Londrillo and Del Zanna 2000, 2004) to correctly treat the solenoidal condition during the magnetic field evolution and it is able to handle the ideal and the dissipative set of MHD equations (Landi et al. 2008) by using a large set of high-order methods for reconstruction, derivation and interpolation of the conservative quantities. The effect of using different schemes to study, for instance, the tearing instability is illustrated in Fig. 3. Without adding any explicit diffusivity, with a small dose of perturbations, magnetic field fluctuations grow in time unless very high order implicit schemes (the C-7th in the specific case) are used. Implicit schemes better resolve spectral properties at smaller scales than explicit methods do (Lele 1992), although they are more computational expensive. Furthermore they are able to reduce considerably the numerical diffusion with

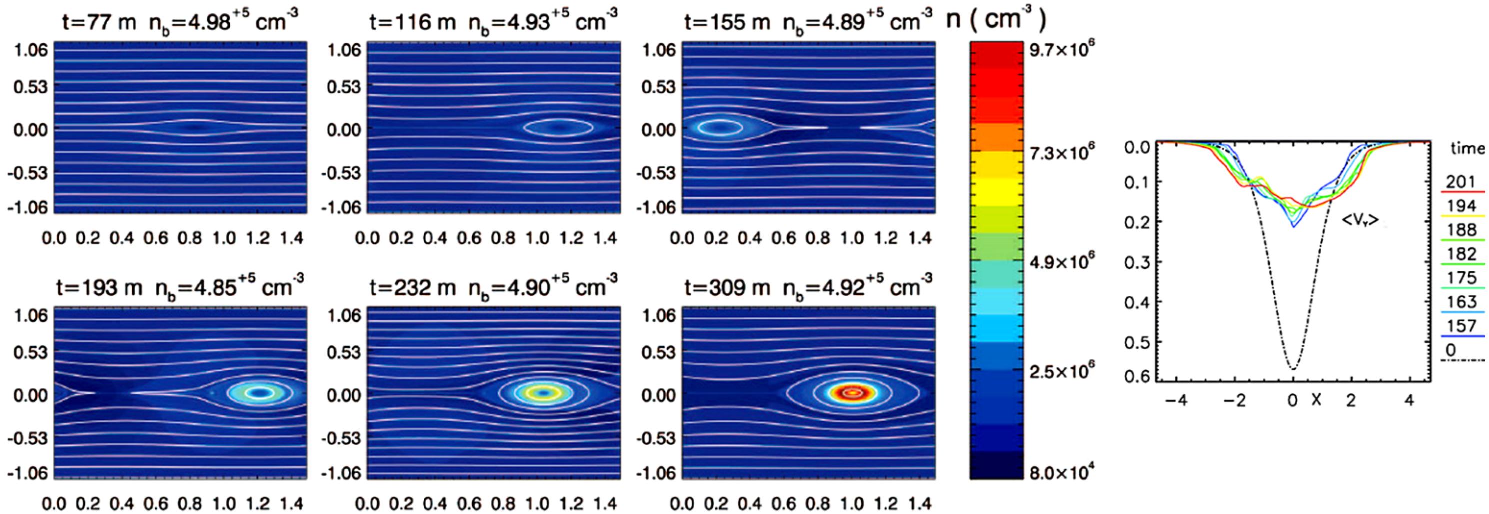

Fig. 2 *Left panel*: Formation of a magnetic island and subsequent acceleration in an expanding-box (Grappin et al. 1993) simulation of the resistive instability including the effect of the melon seed force (Rappazzo et al. 2005). *Right panel*: Disruption of the differential velocity in the non-linear evolution of the resistive, Kelvin-Helmholtz instability (adapted from Bettarini et al. 2006)

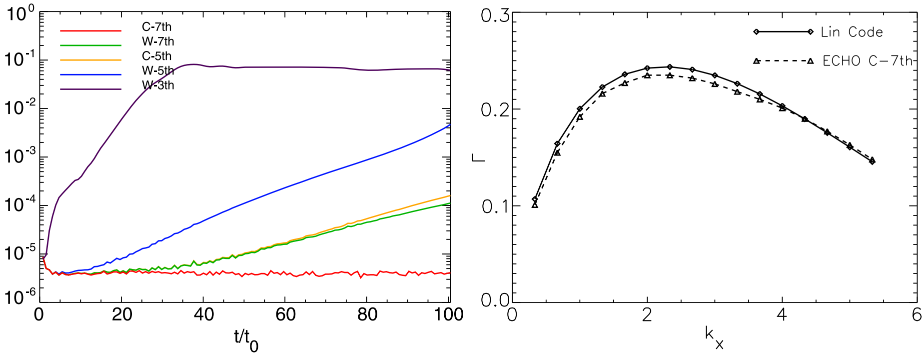

Fig. 3 *Left panel*: The growth rate of the magnetic field fluctuations caused by the numerical noise in a 2D simulation of the tearing instability (adapted from Landi et al. 2008). With very high order numerical schemes, e.g. the 7-th order implicit scheme (C-7th), the numerical dissipation driving a resistive-like instability is sufficiently low to fully appreciate the tearing instability due to the presence of explicit resistivity. The corresponding dispersion relation (*right panel*) well agrees with those predicted by a high-order linear code using pseudo-spectral techniques (Landi et al. 2005, 2008)

respect to explicit schemes of the same order (here we refer to explicit WENO schemes). Implicit schemes are also able to well reproduce the linear phase of the instability (right panel of Fig. 3), while lower order numerical methods introduce a high numerical dissipation such that the resistive instability we intend to simulate is completely canceled out.

4 3D Dynamics of the Current Sheet

The transition to turbulence of a current sheet can change drastically when moving from two to three dimensions. Many hydrodynamics (e.g. Orszag and Patera 1983; Metcalfe et al. 1987) and magneto-hydrodynamics configurations (e.g. Bondeson 1983b; Dahlburg et al. 1992; Dahlburg and Einaudi 2002) can be subjected to the so-called secondary instability. The initial configuration is driven by a two-dimensional instability (primary instability) toward a new configuration that is itself unstable to three-dimensional modes (secondary instability) driving the system towards a turbulent state. In particular in a current-sheet the tearing mode plays the role of the primary instability which can be overwhelmed by ideal modes destabilizing the plasmoid configuration created in the non-linear phase of the resistive instability.

The transition to a turbulent state in three-dimensional configurations has been observed also in frameworks different than resistive MHD. It has been shown that lower-hybrid drift instabilities (e.g. Horiuchi and Sato 1999; Daughton 1999, 2003) dominates the early evolution of the current sheet in the plane perpendicular to the background magnetic field. In the late phase, the non-linear deformation of the current sheet leads to the kinking of the structure at longer wavelengths probably driven by drift-kink instabilities (e.g. Zhu and Winglee 1996; Horiuchi and Sato 1999; Daughton 2002; Lapenta and Brackbill 2002; Lapenta et al. 2003). The presence of a guide-field has the consequence of stabilizing the current-sheet structure against the kinking (Daughton 2003), although a current aligned component of the magnetic field appears to be a necessary ingredient to develop filamentary instabilities observed in recent particle-in-cell simulations (Che et al. 2011).

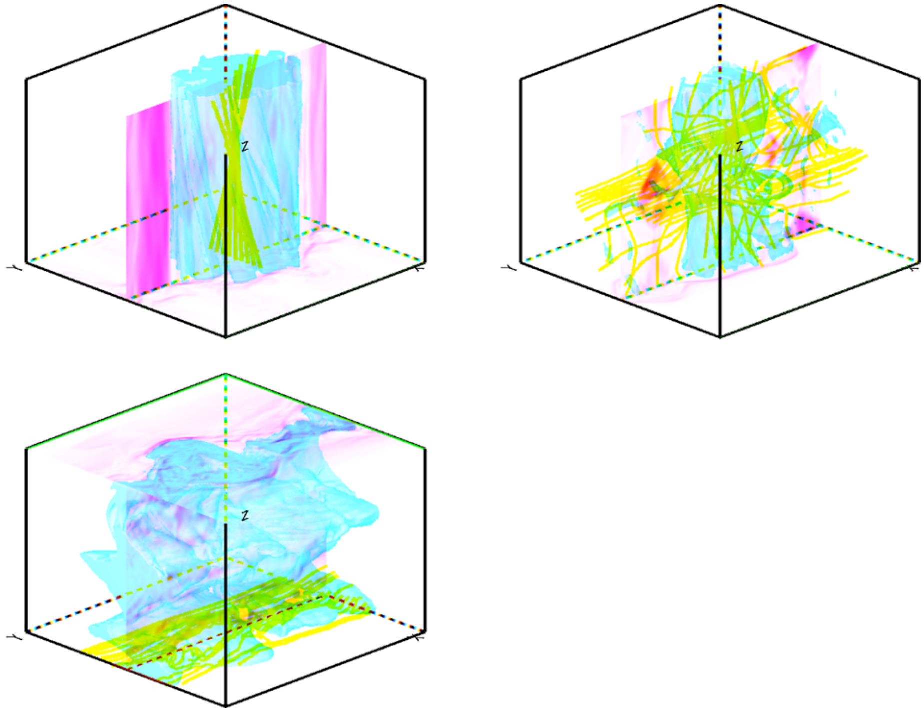

Fig. 4 Density structure (*cyan*), current density intensity (*magenta*) and magnetic field lines (*yellow*) in the non-linear regime for three 3D simulations of the tearing instability for different magnetic field initial conditions. The ideal kink mode destroys the magnetic island formed in the tearing phase (*left bottom panel*) unless a strong guide-field is present (*left top panel*). Rotation inside the current sheet of the magnetic field (*right top panel*) reduces partially the onset of the secondary instability

Dahlburg et al. (1992) studied the development of current-sheet secondary instabilities for a two-dimensional quasi-steady state formed in the saturation phase of the tearing instability. More recently Dahlburg and Einaudi (2002) conjectured and Onofri et al. (2004) showed via incompressible MHD simulations, that the presence of a guide field is able to stabilize the development of the secondary instability. Dahlburg et al. (2005) showed that the onset of the secondary instability is related to the kinking of the magnetic island produced in the non-linear regime of the tearing instability: the presence of a guide-field reduces the twisting of the magnetic field lines and, at a given threshold of the twisting, magnetic flux tubes of the plasmoids become stable against kink-modes (Linton et al. 1996, 1998). The behavior of different initial magnetic field configurations in the non-linear regime is illustrated in Fig. 4 for the case of compressible MHD simulations (Landi et al. 2008): in all panels the density structure (in cyan), the current density intensity (magenta) and the magnetic field lines (yellow) are reported. The top left panel of the figure refers to a simulation where the initial magnetic field is balanced by a pressure gradient and a guide constant magnetic field along the z-direction is present. In this case, the late-evolution of the system is characterized by a quasi-two-dimensional configuration with the presence of a plasmoid, an enhanced current intensity where reconnection takes place, a moderate twisting inside the plasmoid as the result of the presence of magnetic island in the (x, y)-plane, and a strong guide field along the z-direction. A detailed view of the central island in the late evolution of such configuration is shown in Fig. 6, where a clip of magnetic field lines at the center of the numerical domain is shown along with a contour of the density. It is manifest the slight kinking of the guide field whose presence is however sufficient to maintain the magnetically confined density structure: the central plasmoid is preserved and its following evolution is driven by the increase of the velocity eddies (out of the fragmented current sheet structure) which determine the displacement of the overall island. In the absence of the guide-field, the magnetic island is completely destroyed by the kink instability (bottom left panel of Fig. 4) and the system recovers a high chaotic state. A rotation component inside the current sheet, as expected in a force-free initial equilibrium, reduces partially the onset of the secondary instability (left top panel of Fig. 4).

The magnetic field configuration and the competition between primary and secondary instabilities have consequences also in the magnetic energy spectra evolution. Onofri et al. (2004, 2007) studied the spectrum anisotropy in the non-linear regime of the tearing modes in presence of a guide field. The authors observed a strongly anisotropic spectrum with a preferential direction (about 45 deg with respect the current-sheet direction) where magnetic energy is stored. An enlargement of the anisotropy angle is then observed at later stage of system's evolution, maybe related to a late development of secondary modes. A similar behavior has been also observed by Landi et al. (2008) in the case of a pressure equilibrium configuration with a strong guide-field. The spectrum anisotropy is driven directly by the most unstable modes of the primary instability in the linear phase (see left top panel of Fig. 5). The mode we select have the k-vector aligned with the asymptotic magnetic field ($\pi/4$ in the specific case) and a similar trend is also observed for other configurations where the magnetic field is directed parallel to the current sheet (the y direction). The strong difference is in the non-linear regime and it is related to the onset of the secondary instability: since in presence of the guide field the system is stable, primary modes dominate the late stage evolution of the system (bottom left panel of Fig. 5). On the contrary, without guide-field in the non-linear regime (bottom center panel of the same figure), the dynamics is completely dominated by secondary modes: we still observe anisotropic spectra but now the most energetic ones are those in the direction perpendicular to the mean magnetic field (the modes driving the kink instability of the magnetic islands). In the force-free initial configuration, the rotational component inside the current sheet partially reduces the secondary instability and this is reflected in the Fourier space by the presence of energetic modes in both directions. A similar dynamics is also observed in presence of a sheared flow (Bettarini et al. 2009) (see below).

5 3D Dynamics of a Current Sheet Embedded in a Shear Flow

The three dimensional evolution of a current sheet embedded in a shear flow (current-vortex sheet configuration) has not been extensively studied in the past. Dahlburg and Einaudi (2001) studied the development of secondary ideal modes for an initial configuration near the saturation condition of the primary instability. Compressibility effects in the development of the primary instability were analyzed in two-dimensional (Dahlburg and Einaudi 2000) and three-dimensional (Dahlburg et al. 2001) configurations.

Bettarini et al. (2009) studied the linear and non-linear evolution of such configurations by varying the orientation of the magnetic field forming the current-sheet with respect the sheared flow direction, generalizing the two-dimensional study of Bettarini et al. (2006). The configurations they used are sketched in Fig. 7 and intended to study the wake profile of the fast-slow solar wind formed above sun's helmet streamer, the sheared flow being assumed to be supersonic and subalfvènic, while the thickness of the current sheet being much smaller than the thickness of the shear.

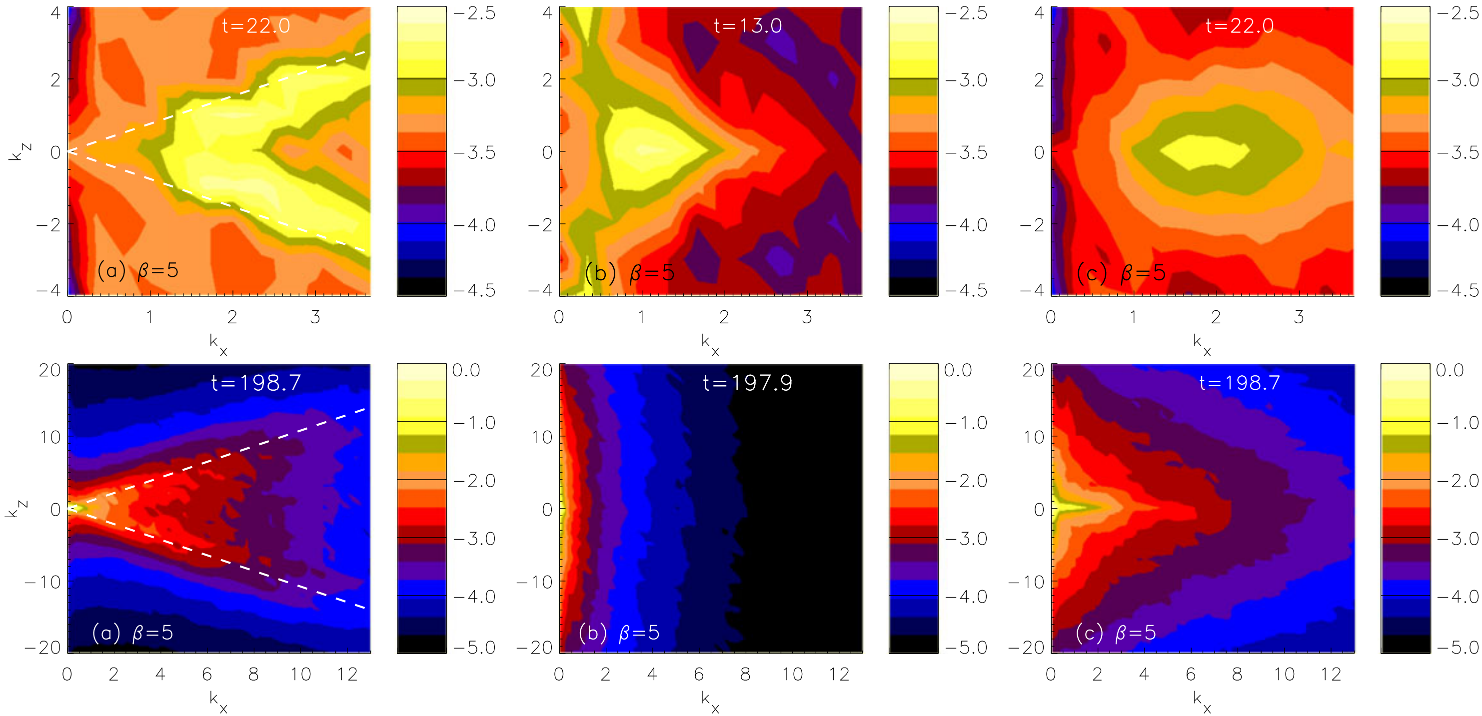

Fig. 5 Magnetic field spectra in the linear (*top panels*) and non-linear (*bottom panels*) regime of the tearing instability of a current sheet. Each panel refers to a different magnetic field initial configuration which forms the current sheet. The x-direction corresponds to the direction of the magnetic field far away from the current sheet

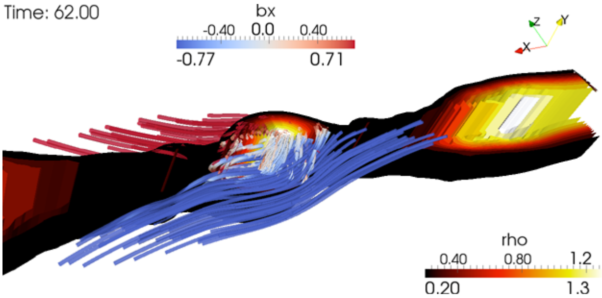

Fig. 6 Detail of the central magnetically-confined higher-density region: clip along the x–y plane of the density contour along with the magnetic field *lines colored* according to the x-component of the magnetic field is shown. The guide field is robust enough to preserve the whole structure against secondary instabilities

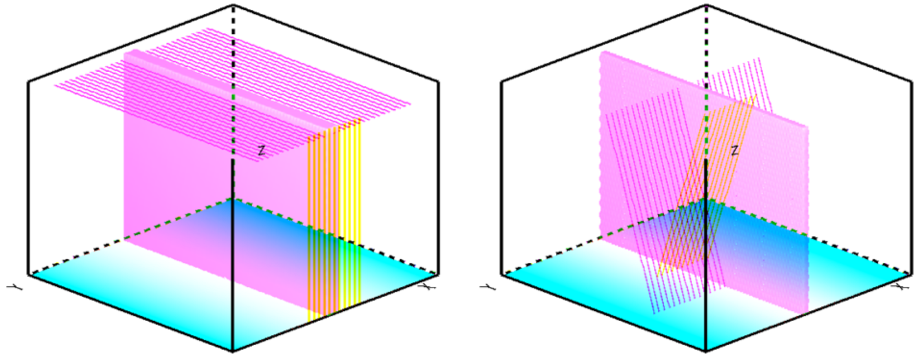

Fig. 7 Initial conditions for a numerical experiment on the dynamics of a current-sheet embedded in a shear flow: Magnetic field lines are encoded in *magenta*, the shear flow is outlined in *cyan*, current density field lines are *yellow*. The *magenta* structure at the center of the numerical domain is the pressure. We present two cases: the magnetic field is along the wake direction (y-direction) (*left panel*); the magnetic field forms an angle of $\pi/4$ with respect the wake in the y–z plane (*right panel*)

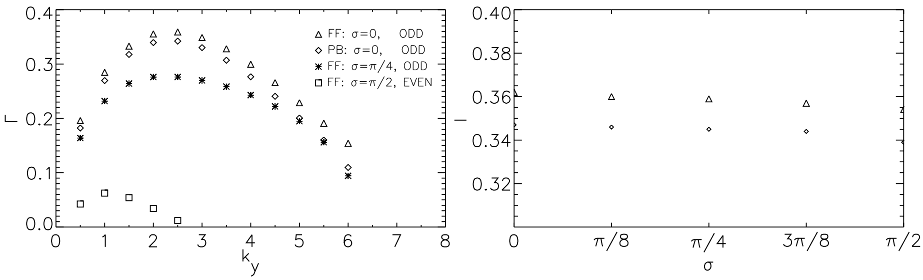

Fig. 8 *Left panel*: Dispersion relation for a force-free (FF) and a pressure balanced (PB) initial configuration of a "current sheet *plus* wake" structure as described in the text. The curve are obtained by means of a two-dimensional linear code. σ measures the angle between the magnetic field and the basic flow. *Right panel*: maximum growth rate of the primary instability in three-dimensional simulations as function of σ. The initial configuration is the same as the two-dimensional case shown in the *left panel*

The linear evolution of this structure in two dimensions revealed that resistive modes triggered by the tearing reconnection of the current sheet dominate for all but one of the initial magnetic field configurations: the growth rate of the resistive instability decreases as the angle of the magnetic field with the flow increases and, for $\sigma = \pi/2$, i.e. when magnetic

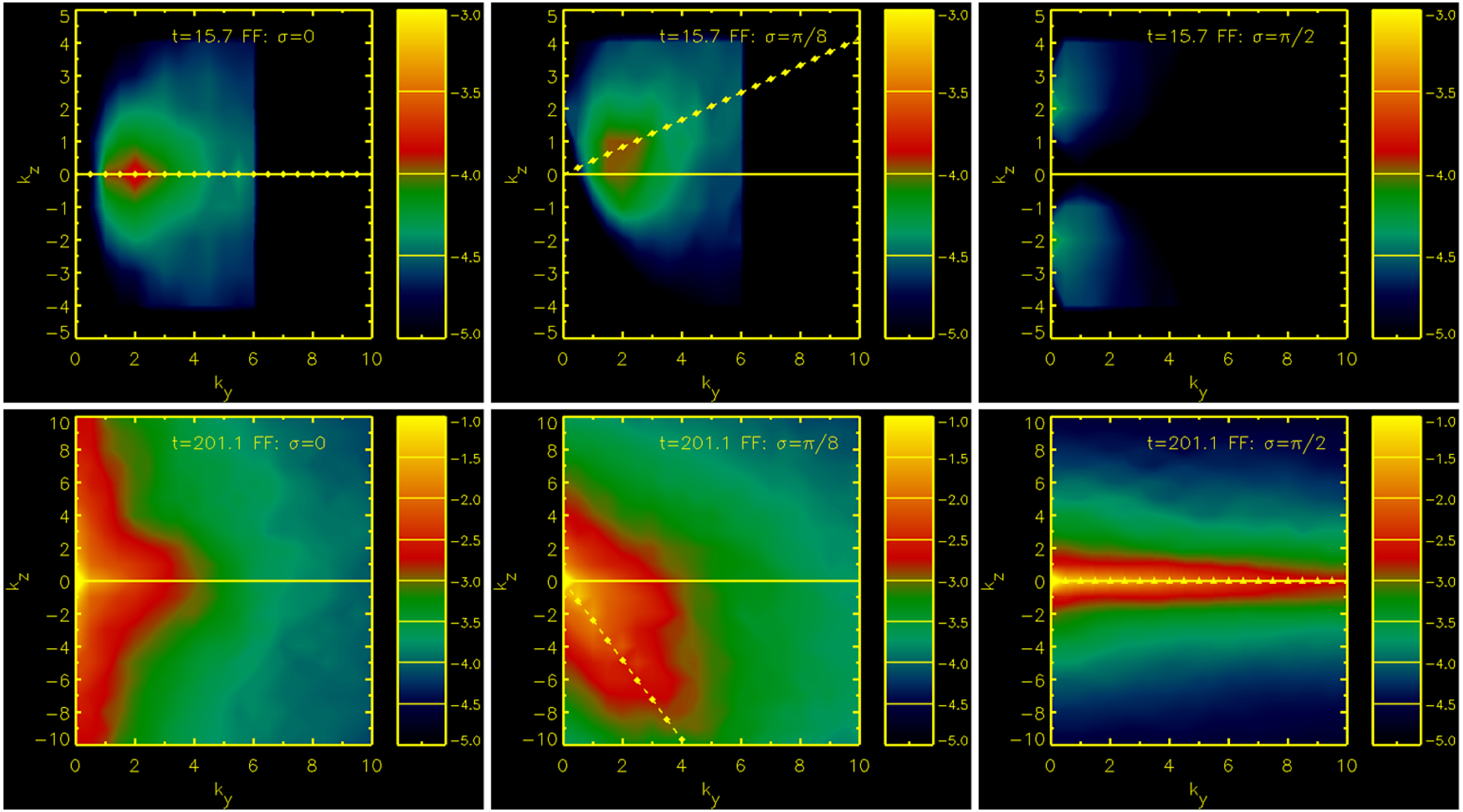

Fig. 9 Magnetic energy spectra for three simulations of the current-vortex sheet destabilization in the linear (*top*) and non-linear (*bottom*) regime. All three simulations are characterized by an initial force-free equilibrium. The differences stem from the asymptotic magnetic field orientation with respect to the shear flow

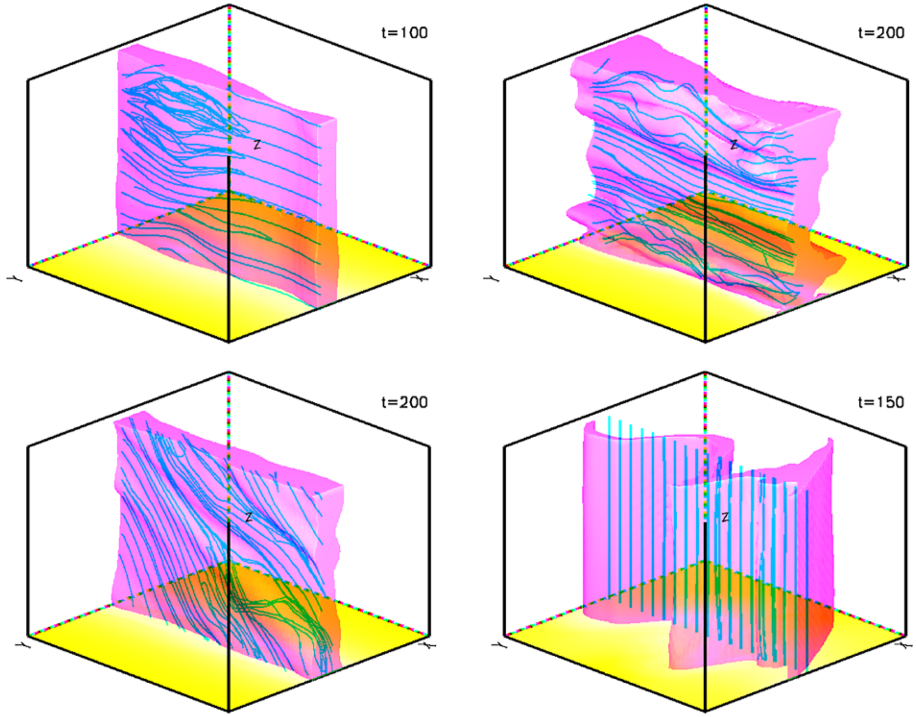

Fig. 10 Pressure structure (*magenta*), magnetic field lines (*blue*) and shear flow contour (*yellow*) for different simulations of the current-vortex sheet destabilization. All simulations refer to a pressure balanced magnetic field equilibrium with different orientations of the magnetic field with respect to the flow. *Top left*: case with $\sigma = 0$ (magnetic field parallel to the flow) at the end of the linear regime ($t = 100$). *Top right*: same simulation at $t = 200$. *Bottom left*: simulation with $\sigma = \pi/4$ at $t = 200$. *Bottom right*: simulation with $\sigma = \pi/2$ (magnetic field perpendicular to the flow) at $t = 150$

field lines are initially perpendicular to the flow, the ideal Kelvin-Helmholtz-like instability prevails (see Fig. 8, left panel). Three-dimensional simulations allow the ignition of all the instability modes and, in particular of the modes orthogonal to the basic flow. As a consequence, all cases are characterized by the development of varicose-resistive modes with almost same growth rates (Fig. 8, right panel). A further inspection of the spectra during the linear phase revealed that the most growing modes are those having a specific direction, corresponding to the direction of the asymptotic magnetic field (Fig. 9, first row).

The lack of a stabilizing magnetic field (the guide field) has the consequence to allow the growth of ideal modes in the saturated non-linear dynamics of the system as observed in the case of the pure tearing instability. In all cases, except when $\sigma = \pi/2$ the secondary destabilization is driven by the ideal kink instability: the magnetic islands created during the reconnection process (as those shown in the top left panel of Fig. 10) are completely destroyed with the formation of structures in direction perpendicular to the magnetic field, the direction of the primary resistive modes (Fig. 10, right top end left bottom panels). For the $\sigma = \pi/2$ case, where the system was primarily unstable also to the Kelvin-Helmholtz modes, are the last which overwhelm the resistive modes (see the bottom right panel of Fig. 10). In the Fourier space the dominance of the secondary instability in the late evolution of the system is always characterized by a spectrum where the energy is mainly concentrated in modes directed perpendicularly to the mean magnetic field (Fig. 9, bottom rows).

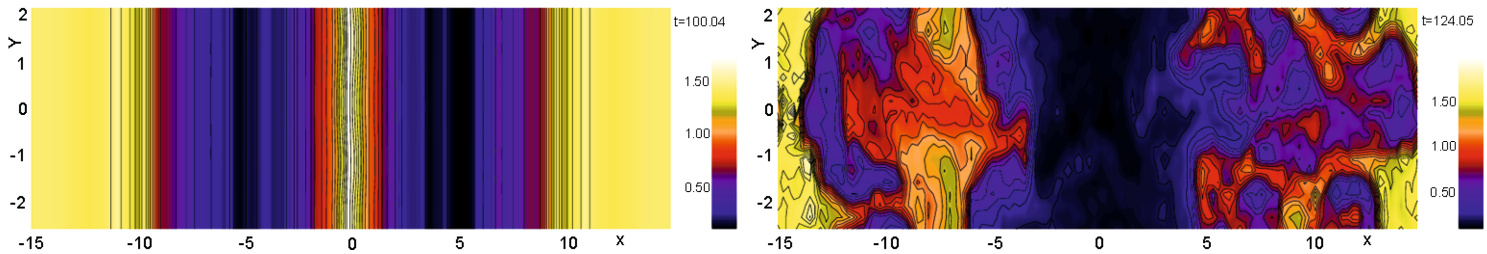

Fig. 11 Two dimensional clip of the density in a three-dimensional box for a simulation of a current-sheet evolution without guide field at $t \approx 100$ and $t \approx 124$ (t is the simulation time). The *left panel* show the end state of the tearing-driven reconnection *plus* coalescence evolution of the initial current sheet: the state is kinking unstable and it will evolve to a final chaotic state (*right panel*) passing through a interchange instability phase

6 Conclusions

As observed in the present review, the evolution of a current and/or a current-vortex sheet critically depends on the overall structure of the magnetic field. The three-dimensional linear and non linear evolution allows to come into picture several different instabilities, with their relative driving modes, which determine the final fate of the initial equilibrium state. Such properties of the three-dimensional evolution have consequence on the interpretation of structures observed in the heliosphere. For instance, the plasma ejecta observed in the top of the helmet streamer, if interpreted in terms of coalesced structures created by resistive instabilities of the heliospheric current sheet, must be stabilized in some way to avoid the natural insurgence of secondary ideal modes.

Different phenomena in astrophysics and within the heliosphere show signs and peculiarities of such dynamics such as, for instance, the magnetic-to-kinetic energy transfer process observed in jets emitted from accretion disks around forming stars or black holes: there the jet dynamics critically depends on the interplay of perturbations developing along the magnetic field lines and across them, a process possible only in three-dimensional configurations like the one described in Sect. 4 without guide field (Lapenta and Bettarini 2011b). Another example can be processes like Earthward and tailward depolarization front evolution connected to substorm events which are unstable to the interchange instability. Recent MHD numerical simulations of magnetotail current sheet and consequent depolarization front dynamics show different instability regimes (unsteady reconnection, kinking instability, interchange instability) leading to a final very turbulent state (Lapenta and Bettarini 2011a; Guzdar et al. 2010) as reported in Fig. 11 displaying a two-dimensional clip of the density at the center of three-dimensional box. The left panel shows a density stratification with the depolarizations fronts at the sides of the clip: such configuration is unstable to the kinking instability that will drive the interchange instability evolutions of the fronts producing pillars that are stretching and mixing till a final chaotic state.

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