ELECTRON-ONLY MAGNETIC RECONNECTION IN PLASMA TURBULENCE

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Abstract

We present hybrid-Vlasov–Maxwell simulations of magnetized plasma turbulence including non-linear electron-inertia effects in a generalized Ohm’s law. When fluctuation energy is directly injected on a wide range of scales that include those near the ion-kinetic scales, the ions efficiently become de-magnetized around rapidly forming electron-scale current sheets. These are the current sheets where electron-only reconnection efficiently occurs. We show that these electron-only reconnection events are characterized by electron jets unaccompanied by ion outflows, similar to those found in recent MMS measurements reported in [Phan et al. (2018)] that were taken in the Earth’s turbulent magnetosheath downstream of the bow shock. We also demonstrate that the physics of reconnection within these current sheets and the accompanying turbulent dynamics at sub-ion scales is consistent with an electron-magnetohydrodynamic description. We conjecture that this kind of turbulent regime may be found in systems where plasma processes, such as velocity-space instabilities and/or shocks, modify the cascade by injecting energy close to the ion-kinetic scales.

1. INTRODUCTION

The solar wind and the Earth’s magnetosphere are the best natural laboratories for studying the fundamental physics of weakly collisional, magnetized plasmas [Bruno & Carbone 2013]. Our knowledge and understanding of these environments is based on highly accurate \textit{in situ} satellite measurements of plasma fluctuations and particle distribution functions, revealing the detailed properties of plasma turbulence (e.g., Alexandrova et al. 2009; Sabraoui et al. 2009; Chen & Boldyrev 2017) and magnetic reconnection (e.g., Retino et al. 2007; Burch et al. 2016). Space missions such as Cluster and MMS provide unprecedented opportunities to investigate multi-scale plasma physics, from the ion-kinetic scales down to the electron-kinetic scales and beyond, and thereby constrain theoretical models of kinetic turbulence.

By contrast with hydrodynamical (fluid) turbulence, turbulence in weakly collisional, magnetized plasmas involves a complex interplay between myriad physical regimes delineated by disparate scales (Schekochihin et al. 2009). Above the ion- and electron-kinetic scales, the turbulence is “magneto-fluid”, behaving qualitatively similar to turbulence in collisional, magnetized fluids. However, as the turbulence cascades down to the ion and electron scales, several plasma-kinetic processes become simultaneously important and compete in a six-dimensional phase-space cascade of free energy (e.g., Schekochihin et al. 2008; Servidio et al. 2017; Adkins & Schekochihin 2018; Cerri et al. 2018; Pezzi et al. 2018; Eyink 2018; Kawazura et al. 2019). Furthermore, non-local energy transfer can be mediated by magnetic reconnection (see, e.g., Cerri & Califano 2017; Franci et al. 2017), and a variety of instabilities driven by anisotropy in the particle distribution function can inject fluctuations on a range of scales (see, e.g., Marsch 2006; Wicks et al. 2010; Matteini et al. 2012; Kunz et al. 2014, 2018).

Regarding the former, magnetic reconnection plays an important role in systems where ion-kinetic current sheets (CSs) are continuously generated and disrupted by turbulent motions, as observed by satellites (Retino et al. 2007; Sundkvist et al. 2007; Vörös et al. 2017) and in numerical simulations (Matthaeus & Lamkin 1986; Servidio et al. 2009, 2012; Perrone et al. 2013, 2018; Karimabadi et al. 2013, 2014; Zhdankin et al. 2013; Franci et al. 2016; Cerri et al. 2016, 2017a; Valentini et al. 2016; Wan et al. 2016; Shay et al. 2018). In this situation, reconnection can modify or even short-circuit the otherwise continuous energy transfer from fluid to kinetic scales (Loureiro & Boldyrev 2017; Mallet et al. 2017; Cerri & Califano 2017; Franci et al. 2017; Vech et al. 2018), the latter facilitated by a direct injection of energy at scales around and below the ion skin depth $\lambda_i$ and/or the ion Larmor radius $\rho_i$ (see Cerri & Califano 2017; Franci et al. 2017).

In the standard picture, reconnection takes place in an “electron diffusion region” (EDR) embedded within a larger ion-scale CS, driving both ion and electron outflows in an “exhaust” (Shay et al. 1998). Typically the EDR emerges from a direct collapse or from a hierarchy of CSs developing within the initial ion macro-layer (Daughton et al. 2009, 2011; Karimabadi et al. 2013). Surprisingly, MMS has recently given evidence in the turbulent Earth’s magnetosheath of series of electron-scale reconnection events where super-Alfvénic electron jets were never accompanied by ion outflows. They dubbed these events “electron-only reconnection” (Phan et al. 2018) to differentiate them from the usual (fast) collisionless reconnection process including electron-scale current layers (see e.g., Coppi 1964; Drake & Kleva 1991; Ottaviani & Porcelli 1993; Drake et al. 1997). It is difficult to explain these results in the context of a turbulent cas-

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In this paper, we investigate whether electron-only reconnection (hereafter, e-rec) can develop in a large-scale turbulent system, using 2D-3V hybrid-Vlasov–Maxwell (HVM) simulations of freely decaying plasma turbulence. These simulations include electron-inertia terms in a generalized Ohm’s law (Valentini et al. 2007), allowing the decoupling of the magnetic field from the ion dynamics at ion-kinetic scales and a complete unfreezing of magnetic flux at the electron-inertial scale. Our main finding is that, when turbulent energy is injected sufficiently close to the ion-kinetic scales (isotropically in k⊥, in our case), e-rec occurs in a way quantitatively similar to that seen in the recent MMS observations (Phan et al. 2018). These reconnection processes involve only the electron dynamics; that is, we find that e-rec is not a multi-scale process in which an EDR is embedded within a larger ion-diffusion region. On the other hand, we also find that the same simulations but where energy is injected farther away from the ion-kinetic scales do not show e-rec processes, recovering the standard multi-scale reconnection process. We therefore conjecture that there is a mechanism in the magnetosheath (e.g., instability and/or locally generated large-amplitude fluctuations) that injects energy close enough to ion-kinetic scales to produce electron-scale CSSs and e-rec processes. We further show that the physics of e-rec is well described by the electron magnetohydrodynamics (Kingson et al. 1987; Bulanov et al. 1992; Mandt et al. 1994).

2. METHOD OF SOLUTION

2.1. Basic equations

We adopt the so-called hybrid-Vlasov–Maxwell (HVM) model, which integrates the Vlasov equation on a phase-space grid for the evolution of the ion distribution function, \( f_i(x, v, t) \), and Faraday’s law for the evolution of the magnetic field, \( B(x, t) \) (Mangeney et al. 2002):

\[
\frac{\partial f_i}{\partial t} + v \cdot \nabla f_i + (E + v \times B) \cdot \nabla v f_i = 0, \quad (1)
\]

\[
\frac{\partial B}{\partial t} = -\nabla \times E. \quad (2)
\]

These equations are coupled to a generalized Ohm’s law for the electric field \( E(x, t) \) that includes the inertia of an isothermal, isotropic electron fluid (Valentini et al. 2007):

\[
(1 - d_e^2 \nabla^2) E = -u_e \times B - T_e \nabla \ln n + d_e^2 \nabla \cdot \left[ n (u_i - u_e) - u_e \right]. \quad (3)
\]

All equations are normalized with respect to the ion quantities: the mass \( m_i \), charge \( e \), inertial length \( d_i \), and cyclotron frequency \( \Omega_{ci} \). The electron fluid is characterized by a finite electron skin depth, \( d_e = \sqrt{m_e/e m_i} \); a flow velocity, \( u_e = u_i - J/n \); and a constant and isotropic electron temperature, \( T_e \). Quasi-neutrality is assumed, \( n_i \simeq n_e = n \), and the current density \( J = \nabla \times B \) (i.e., the displacement current is neglected in Ampère’s law). The number density \( n \) and the ion momentum density \( n u_i \) are computed as the zeroth and first velocity-space moments of \( f_i \), respectively.

2.2. Electron magnetohydrodynamics at sub-ion scales

As turbulent fluctuations cascade to smaller and smaller scales, their frequencies increase, eventually exceeding those described by the MHD approximation. Below ion-kinetic scales, the electron fluid eventually decouples from the ion dynamics. As a result, spatial derivatives of the (number) density \( n \) and of the ion bulk flow \( u_i \) can be neglected. This regime is known as the electron magnetohydrodynamics (EMHD). In this limit, Eq. (3) reduces to Eq. (7) of Bulanov et al. 1992, which governs the collisionless EMHD dynamics, and the field \( \mathbf{B}' = B - d_e^2 \nabla^2 \mathbf{B} \) (rather than \( \mathbf{B} \), as in ideal MHD) is frozen into an incompressible electron flow. Under these conditions, at sub-ion-kinetic scales the current is carried predominantly by the electrons, \( u_e \approx -J/n \). Moreover, in 2D the magnetic field can be written as \( \mathbf{B} = e_x \times \nabla \psi + \mathbf{B}_z \), where \( \psi \) is the flux function; collisionless EMHD then ensures the Lagrangian conservation of \( \psi = \psi - d_e^2 \nabla^2 \psi \) in the electron-fluid frame (Bulanov et al. 1992). Therefore, the HVM model adopted here can correctly capture the EMHD regime at sub-ion scales through the generalized Ohm’s law (3), while simultaneously retaining the fully kinetic ion response.

2.3. Simulations setup

We consider a \( \beta_i = \beta_e = 1 \) proton-electron plasma with a reduced mass ratio of \( m_i/m_e = 144 \), so that \( d_i \gg d_e \) are well separated. The HVM equations (1)–(3) are then solved in a 2D-3V phase space with \( 1024^2 \) grid points spanning a real-space domain of size \( L_x = L_y = 20d_i \), corresponding to a uniform spatial resolution \( \simeq 0.06d_i \lesssim 0.7a_e \). The velocity space is sampled by \( 51^3 \) uniformly distributed grid points spanning \([-5, 5]v_{th,i} \), where \( v_{th,i} = \sqrt{\beta_i/2} \) is the ion thermal speed, corresponding to a resolution of 0.2\( v_{th,i} \) in each velocity direction. Three simulations, labeled sim. A, sim. B, and sim. C for convenience, have been performed. All evolve an initially uniform, Maxwellian plasma embedded in an homogeneous out-of-plane magnetic field, \( \mathbf{B}_0 = B_0 e_z \). Decaying turbulence is initialized by imposing additional random, isotropic magnetic-field perturbations, \( \delta \mathbf{B} \). In sim. A, the wavenumbers \( k \) of these perturbations lie in the range \( 0.1 \leq k d_i \leq 0.6 \) with a corresponding rms amplitude of the in-plane magnetic-field perturbations of \( \left| e_x \times \nabla \psi \right|_{\text{rms}} \simeq 0.15 \). These values are chosen so that moderate-amplitude fluctuations are injected on scales close to the ion-kinetic scales, so as to separate the ion and the electron dynamics from the beginning of the simulation (see the discussion in Section 2.2). Indeed, the eddy turnover time associated with the shortest initial wavelength in sim. A is \( \sim 30 \Omega_i^{-1} \). We will show that e-rec events develop throughout the domain already on

1 We note that a reduced mass ratio, which has been shown to affect standard reconnection physics (Le et al. 2013), should be here less of an issue here as long as \( m_i/m_e \) is large enough to allow the electron dynamics to decouple from the ion dynamics.
this timescale, whereas fully developed turbulence is realized only on the eddy turnover time of the outer-scale fluctuations, $\tau \sim 100\Omega_{i}^{-1}$. In sim.B and sim.C, we excite fewer modes whose wavenumbers lie farther away from the ion-kinetic scales, viz., $0.1 \leq kd_i \leq 0.3$, similar to the regime studied in Cerri et al. (2017); Cerri & Califano (2017); Franci et al. (2017). In particular, in sim.B we adopt the same maximum value of the initial fluctuation amplitude as in sim.A, giving $|e_z \times \nabla u|/\text{rms} \simeq 0.21$. In sim.C, we adopt the same rms value of the magnetic fluctuations as in sim.A. We will show that the initial wavenumber range that distinguishes sim.A from sim.B and sim.C is the critical parameter governing the transition from a regime dominated by “standard” reconnection to a regime dominated by e-rec events. In other words, the presence of wavelengths close to $d_i$ (and not emerging from a cascade at larger wavelengths) is the physical driver of the process dubbed electron-only reconnection. How these “initial fluctuations” might be generated in a magnetized turbulent plasma is a question under investigation.

3. RESULTS

We first describe the results from sim.A. In Fig. 1, top left, we show a full-box view of the out-of-plane current density $J_z$ at $t = 42.5\Omega_{i}^{-1}$. (For comparison, in the right top frame, we show the same quantity from sim.C, which is discussed later on.) We observe the formation of several electron-scale CSs, e.g., CS1 (indicated by the rectangle box) at $(x, y) = (58, 11)$, CS2 at $(23, 11)$, and CS3 at $(21, 36)$. All CSs we have analyzed are characterized by widths $\ell \approx (4–6)d_i \ll d_i$, which are much smaller than those typically observed in simulations where the energy injection occurs exclusively at scales (much) larger than the ion-kinetic scales (e.g., $k d_i \lesssim 0.3$; Cerri et al. 2017). Their lengths $L_{CS} \sim 2d_i$ are also much shorter than those typically observed in other turbulence simulations (see Cerri et al. 2017; Cerri & Califano 2017; Franci et al. 2017). On these scales, the electron fluid, and thus the magnetic field, is expected to decouple from the ions; it is only deep within these thin CSs that the electron fluid ultimately decouples from the magnetic field. These features are shown in Fig. 1 bottom frame, which displays $J_z$ (black), $E_z' \equiv E_z + (u_e \times B)_z$ (red), and $E_z + (u_i \times B)_z$ (blue) versus $y$ at $x \simeq 58d_i$ (corresponding to the vertical dashed line in the accompanying top panel). While the electron fluid is seen to decouple from the magnetic field only deep within CS1 (at $y \simeq 11d_i$, where $E_z' \neq 0$), the ions are approximately decoupled over much of the simulation domain (i.e., $E_z + (u_i \times B)_z \neq 0$ appreciably occur at all scales). The width of CS1, inferred by the condition $|J_z| > J_{\text{rms}}$, turns out to be $\ell \simeq 4d_i$, corresponding to the physical range on which e-rec has been observed.
to occur in the magnetosheath (Phan et al. 2018).

Figure 2. From sim A. Zoom-in on CS1 at \( t = 42.5\Omega_{\text{i}}^{-1} \), (top) Shaded iso-contours of the out-of-plane magnetic field \( B_z \) with superposed iso-contours of \( \psi \) (dashed white) and \( F \) (black). (bottom) Shaded iso-contours of the \( x \)-component of the electron flow, \( u_{e,x} \), and of \( \psi \) (solid black lines). Dashed vertical lines trace the two virtual spacecraft trajectories shown in the two columns of Fig. 3.

Fig. 2 zooms in on CS1 after the onset of e-rec and the formation of an active X-point structure at \( t = 42.5\Omega_{\text{i}}^{-1} \). The top panel reveals a quadrupolar structure of \( B_z \) near the CS, known to be caused by the Hall term (i.e., ion-electron drift, see Uzdensky & Kulsrud 2006). Iso-contours of the flux function \( \psi \) (dashed white lines) and of the corresponding EMHD invariant \( F \) (black lines) coincide on scales larger than \( d_e \), where electron inertia is unimportant. Both quantities advected by the flow are well conserved everywhere except around the X-point, where \( \psi \) locally breaks (and reconnects) on scales \( \sim d_e \). This separation of the \( \psi \) and \( F \) iso-contours is a signature of the EMHD regime (see, e.g., Attico et al. 2002). Indeed, in the bottom panel of Fig. 2 the \( x \)-component of the electron flow \( u_{e,x} \) shows the typical electron jet structures coming out from the X-point (highlighted by \( F \), the solid black lines). No evidence of corresponding ion outflows is found in the exhaust around the X-point.

In Fig. 3 we show data taken from two virtual spacecraft passing through CS1 along the paths traced by the vertical dashed lines in Fig. 2. These trajectories are chosen to be similar to those taken by MMS in Phan et al. (2018). In panels (a) and (f), we show the reversal of \( B_z \) over a few \( d_e \), highlighted by the vertical dashed lines corresponding to the CS1 boundaries (given by the condition \( |J_z| > J_{\text{rms}}^{(\text{sol})} \)). Within these boundaries, there are clear signatures of oppositely oriented electron jets, identified as the exhausts (panels (b) and (g)), without any noticeable corresponding ion outflows (panels (c) and (h)). This feature is in agreement with MMS measurements (Phan et al. 2018). Note that ion jets do not appear even if we move the spacecraft trajectories further away from the X-point location. The parallel electric field \( E_{\parallel} \), the \( z \)-component of the electric field in the electron reference frame, \( E_z = E_{\parallel} + (u_e \times B)_z \), and the dissipation rate, \( \mathbf{J} \cdot \mathbf{E}^* \), all depart significantly from zero only across the CS (panels (d), (e), (i), and (j)). Although \( \mathbf{J} \cdot \mathbf{E}^* \) oscillates, its integral across CS1 is positive, indicating the possibility of a region of net magnetic-to-particle energy conversion (our equations only allow conversion into electron bulk, rather than thermal, energy). All of these features seen in CS1 are observed also in the other CSs.

That the dynamics of these CSs may be described accurately by EMHD is also supported in Fig. 3 by the spectra of the solenoidal \( u^{(\text{sol})} \) and irrotational \( u^{(\text{irr})} \) contributions to the in-plane ion and electron velocities (compared with the spectrum of the in-plane magnetic field). These spectra demonstrate that the ion flow is almost incompressible in the range \( d_e^{-1} < k_{\perp} < d_e^{-1} \), while the electron flow remains nearly incompressible across an even larger range. We have also verified that the solenoidal contribution to \( u_{e,\perp} \) around the CSs largely dominates over its irrotational counterpart, and that the “EMHD terms” in our generalized Ohm’s law dominate the dynamics (viz., \( |\nabla \cdot (n_{i}\mathbf{u}_{i,x})| \ll |\nabla \cdot (n_{e}\mathbf{u}_{e,z})| \) and \( |n_{e,z} (\nabla \cdot \mathbf{u}_{e})| \ll |\mathbf{u}_{e} \cdot \nabla (n_{e,z})| \); see, e.g., Bulanov et al. 1992).

The role of ions in the fully developed turbulent regime \( (t \gg \tau) \) has been further investigated by comparing the pattern of out-of-plane and in-plane electron and ion flow velocities (see Fig. 5). This is done at \( t = 114\Omega_{\text{i}}^{-1} \), after the rms perpendicular current \( J^{(\text{rms})} \), a proxy for turbulent activity, reaches its maximum value (not shown here; see e.g., fig. 1 of Servidio et al. 2015). At this moment, the magnetic and electric energy spectra show power laws close to \(-3 \sim -1\), respectively, in the range \( d_e^{-1} \lesssim k_{\perp} \lesssim d_e^{-1} \) (not shown here), in agreement with previous gyro-kinetic, hybrid-kinetic, and fully kinetic simulations (Howes et al. 2011; TenBarge et al. 2012; Told et al. 2015; Franci et al. 2015, 2016, 2018; Cerri et al. 2016; Groˇselj et al. 2017, 2018; Arzamasskiy et al. 2019) and satellite measurements (Alexandrova et al. 2008; Sahraoui et al. 2009; Chen et al. 2010; Lacombe et al. 2017). In Fig. 2 we show iso-contours of \(-u_{e,\perp} \approx J_z/n \) (top left), \( u_{i,z} \) (top right), \( u_{e,z} \) (bottom left), and \( u_{i,y} \) (bottom right). All electron quantities exhibit many thin structures at the electron scale, well correlated with the CSs traced by \( J_z \) (not shown here, as it is nearly identical to \(-u_{e,\perp} \)). On the other hand, all of the ion quantities exhibit much smoother variations and, in particular, are largely uncorrelated with the corresponding electron flows or CSs. As in Fig. 2 electron jets are also visible in \( u_{e,y} \) (e.g., at \((x,y) \approx (10,20)d_e\); note that here the jets are along \( y \), while no corresponding ion outflows are apparent.

None of these e-rec features are observed in sim.B and sim.C, in which the magnetic perturbations are injected farther away from \( d_e \), at least up to the time when the turbulence is fully developed, \( t \approx 200 \). In particular, as soon as CSs form in sim.B and sim.C, we observe the development of “standard” reconnection layers embedded
Figure 3. From sim.A. Data taken by two virtual spacecraft passing through CS1 along the paths traced by the vertical dashed lines in Fig. 2 ("Spacecraft 1" at $x \approx 57.4d_i$, left column; and "Spacecraft 2" at $x \approx 58.4d_i$, right column). The vertical dashed lines represent the local boundaries of the CS given by the condition $|J_z| > J_{rms}^z$.

Figure 4. From sim.A. Spectra at $t = 42.5 \Omega_i^{-1}$ of the in-plane magnetic field (blue solid line), the solenoidal contributions to the in-plane ion and electron velocities $u^{(sol)}_{i,e}$ (orange and red solid lines, respectively), and the irrotational contributions of the same velocities $u^{(irr)}_{i,e}$ (green and black-dashed curves, respectively). Reference slopes of $-1$ and $-3$ slopes are provided.

This is shown for sim.C in the right panels of Fig. 4 (the same holds for sim.B, not shown here), where we show a full-box view of the out-of-plane current density $J_z$ at $t = 95 \Omega_i^{-1}$. We see the formation of a CS located at $x = 18$, $y = 50$ (highlighted by the black square). As in sim.A, the CS thickness collapses down to the $d_e$ scale at the X-point. However, now its length along the in-plane magnetic field is much bigger (more than $10d_i$) than those of the CSs observed in sim.A (left panels). As a consequence, at a sufficiently large distance from the X-point, ions can couple to the magnetic-field/electron dynamics and ion outflows are generated. This is shown quantitatively in the bottom-right panel (data $v$s. $y$ taken along the dashed line): by way of comparison with its sim.A counterpart (bottom-left panel), the ions are seen to be better coupled to the magnetic field away from the CS. This facilitates the ions’ participation in the reconnection exhaust; indeed, a zoom-in of this CS (see Fig. 6) shows the X-point structure with the electron exhaust embedded within an ion outflow.

To give further evidence that the exhausts are made up of two coupled ion-electron jets, in Fig. 7 we show six successive plots of the electron and ion outflow measured to the right of the X-point of the CS shown in Fig. 6. This
sequence shows a central, well-collimated, strong electron jet (continuous lines) which becomes less collimated farther out from the X-point. We also observe a smoother and less intense ion jet superposed to the electron one (dashed lines).

Such an electron-ion structure is never observed in sim.A, in which the ions decouple from the magnetic-field and electron dynamics over nearly the entire simulation domain (see Fig. 1 bottom left frame, and Fig. 2 right frame). This difference is observed not only when the first active CSs form, but also at later times when the turbulence is fully developed. We also note that although the ion-electron coupling remains valid in the fully developed turbulence stage of Sim.C, some electron-scale structures seem to emerge, see Fig. 2 right frame. However, these electron-scale structures are embedded in a hierarchy of larger, ion-scale structures, as previously found in Karimabadi et al. (2013). We stress that in Sim.A we do not find this kind of hierarchy, but only e-rec events take place.

In summary, if energy is injected in the range $0.1 \leq kd_i \leq 0.3$ (as in sim.B and sim.C), longer CSs are generated and “standard” reconnection develops. But, if energy is injected at larger wavenumbers $0.1 \leq kd_i \leq 0.6$ (as in sim.A), then CSs are shorter and ions are decoupled from the magnetic-field/electron dynamics almost everywhere. As a result, ion outflows are never observed in sim.A where only electrons participate in the reconnection dynamics (following nearly incompressible EMHD).

4. CONCLUSIONS AND DISCUSSION

Using HVM simulations that include a model for electron-inertia effects, we have demonstrated for the first time the possibility of electron-only reconnection in plasma turbulence, in which electron exhausts in reconnecting CSs are not accompanied by corresponding ion outflows. The properties of the emergent reconnecting CSs are in good agreement with those “electron-scale” CSs recently measured in the turbulent magnetosheath by MMS (Phan et al. 2018). We find that the absence of corresponding ion outflows in the reconnection exhaust can result from the injection of large-amplitude, broad-band fluctuations near ion-kinetic scales (in our case $\gtrsim 10d_i$). The dynamics of the reconnecting magnetic field is controlled almost entirely by electrons following an EMHD-like dynamics at sub-ion-kinetic scales.

Based on our results and their close resemblance to MMS data, we conjecture that energy injection occurring near ion-kinetic scales, perhaps due to velocity-space instabilities and/or shocks, can qualitatively alter the evolution of CSs and the dynamics of magnetic reconnection in plasma turbulence. The prospect of directly observing such dynamics outside of the magnetosheath in the turbulent solar wind should be considered a frontier in the exploration of the heliosphere and the analysis of satellite data.

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Figure 5. Left: From sim.A. Shaded iso-contours of (minus) the out-of-plane electron flow, \(-u_{e,z} \approx J_z/n\) (top left); the out-of-plane ion flow, \(u_{i,z}\) (top right); and the \(y\)-component of the electron and ion flow, \(u_{e,y}\) and \(u_{i,y}\) (bottom left and bottom right, respectively) in a zoom-in region one-fourth the size of the sim.A domain at \(t = 114\Omega_i^{-1}\). Right: From sim.C. Shaded iso-contours of (minus) the out-of-plane electron flow, \(-u_{e,z} \approx J_z/n\) (top left); the out-of-plane ion flow, \(u_{i,z}\) (top right); and the \(x\)-component of the electron and ion flow, \(u_{e,x}\) and \(u_{i,x}\) (bottom left and bottom right, respectively) in a zoom-in region one-fourth the size of the sim.C domain at \(t \approx 203\Omega_i^{-1}\).

Figure 6. From sim.C. In-plane velocity vector field for electrons (left) and ions (right) with superimposed the flux function \(\psi\) iso-contours around the X-point at \(x \approx 6d_i, y \approx 56d_i\), at \(t = 105\Omega_i^{-1}\).
Figure 7. From sim.C. Cuts vs. $y$ of the rightward outflow from the X-point shown in Fig. 6 at $t = 105\Omega_i^{-1}$. The $x$-component of the electron (solid) and ion (dash-dotted) velocities are plotted vs. $y$ at different $x$ values starting close to the X-point and going as far away as $3d_i$.

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