Supporting Information for "Magnetotail Ion Structuring by Kinetic Ballooning-Interchange Instability"

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Introduction

PIC Simulation Setup

The present investigation employs a 3-D PIC simulation model that retains the full dynamics for both electrons and ions. The initial magnetic field configuration is similar to those considered previously in [Pritchett and Coroniti, 2010, 2013] and is described by the vector potential $A_0(x,z)$ given by

$$A_0(x,z) = B_0 L \ln \{ \cosh [F(x)(z/L)] / F(x) \},$$

where $F(x)$ is a slowly varying but otherwise arbitrary function. For a nonconstant $F(x)$, there is a finite $B_z$ field, which at the center of the current sheet has the form

$$B_{0z}(x,0) = -B_0 LF'(x)/F(x).$$

The specific configuration used in the present study is illustrated in Figure S6. Figure S6a shows the 2-D $(x,z)$ magnetic field configuration, and Figure S6b shows the initial equatorial magnetic field profile $B_{0z}(x,0)$. The BICI modes will be excited in the region of the tailward gradient in $B_z$ ($20 < x/\rho_{i0} < 28$), which corresponds to a region of decreasing entropy as $x$ increases tailward [Schindler and Birn, 2004; Pritchett and Coroniti, 2013]. Here, $\rho_{i0}$ is the ion gyroradius in the asymptotic lobe $B_0$ field.

Previous PIC simulations of BICI generation [Pritchett and Coroniti, 2010, 2013; Pritchett et al., 2014] have considered a charge neutral, generalized Harris configuration in which the ion and electron cross-tail drifts are given by $V_{di} = -2cT_i/eB_0L$ and $V_{de} = 2cT_e/eB_0L$, where $e$ is the magnitude of the fundamental electric charge and $L$ is the half-width of the current sheet. In the present study, we consider a charged current sheet in which the electrons carry all of the cross-tail current with a net drift of $V_{de}^{ch} = 2c(T_i + T_e)/eB_0L$. Since the ions now carry no current, an electric field $E_{0z}(x,z)$ must be present in order to balance the nonuniform ion pressure,

$$E_{0z}(x,z) = -(2T_i/eL)F(x) \tanh[F(x)(z/L)].$$

The (ion) density distribution is given by

$$n(x,z) = n_0 F^2(x) \text{sech}^2[F(x)(z/L)] + n_p,$$
where \( n_0 \) is the characteristic equatorial density at \( x/\rho_0 = 16 \) and \( n_0 = 0.08 n_0 \) is a constant background density. The density distribution for the current-carrying electrons is similar to that for the ions but with a larger characteristic density \( n_e \) given by \( (n_e - n_0)/n_e = [T_i/(T_e + T_r)](V_{ch}/c)^2 \).

The simulation has a grid \( N_x \times N_y \times N_z = 512 \times 1024 \times 256 \) distributed over the ranges \( 0 \leq x/\rho_0 \leq 32.0, 0 \leq y/\rho_0 \leq 64, -8 \leq z/\rho_0 \leq 8 \), so that \( \rho_0 = 16 \Delta \), where \( \Delta \) is the grid spacing. The ion to electron mass ratio is \( m_i/m_e = 64 \), all particle temperatures are equal to \( m_i V_A^2/4 \) (here \( V_A = (B_0^2/4\pi n_0 m_i)^{1/2} \) is a representative Alfvén speed), the electron plasma frequency/gyrofrequency ratio is \( \sqrt{2} \), and the electron Debye length is \( \Delta \). The total number of particles in the simulation is 5.8 billion.

The simulation employs “closed” boundary conditions at the \( x \) boundaries [Pritchett and Coroniti, 1998]. No magnetic flux is allowed to cross these boundaries, corresponding to the condition \( \delta E_x = 0 \), and particles that cross these boundaries are reinserted back into the system in the opposite half \( z \) plane with \( v_x = -v_x \) and \( v_z = v_z \) [Pritchett et al., 1991]. In addition, the perturbed field \( \delta E_x \) is assumed to vanish at these boundaries. At the \( z \) boundaries, conducting conditions are assumed, and particles striking such a boundary are reintroduced in the opposite half \( z \) plane with \( v_x = -v_x \) and \( v_z = v_z \). This symmetric condition on the particle reflection is valid in the absence of a guide magnetic field. Periodicity in the \( y \) direction is assumed for both the particles and fields. The coordinate system used in the simulations has \( x \) increasing tailward (away from the Earth), \( y \) directed dawnward, and \( z \) directed northward. In the simulation figures, the coordinates are expressed in units of \( \rho_0 \).

Caption for Movie S1.

Results from 3D PIC simulation of BICI development in the electron (charged) current sheet as seen in \( B_X \) (a), \( B_Y \) (b) and \( B_Z \) (c) magnetic field components, ion density (d), kinetic ion energy density (e), \( T_{XX} \) (f) and \( T_{XY} \) (g) ion temperature components, \( P_{XY} \) ion pressure tensor component (h), off-plane ion vorticity component \( \omega_{ij} \) (i), and in-plane ion divergence \( \partial V_x/\partial x + \partial V_y/\partial y \) (j) between \( \Omega_{ot}=161 \) and \( \Omega_{ot}=280 \). The contours of \( B_Z \) magnetic field component are overplotted as black curves. The star glyphs at \( (x/\rho_0,y/\rho_0,z/\rho_0)=(10.5,23.0,-1.5) \) (magenta), at \( (x/\rho_0,y/\rho_0,z/\rho_0)=(12.5,22.0,-1.5) \) (blue) and at \( (x/\rho_0,y/\rho_0,z/\rho_0)=(13.5,20.5,-1.5) \) (cyan) denote the location of three virtual spacecraft also discussed in Figure 3 of the manuscript.

References

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Schindler, K., and J. Birn (2004), MHD stability of magnetotail equilibria including a background pressure, J. Geophys. Res., 109, A10208, doi:10.1029/2004JA010537.
Figure S1. Time History of Events and Macroscale Interactions during Substorms probe P3 observations on 19 May 2010 between 12:09:30 and 12:15 UT. From top to bottom are shown: joint SST (full mode) and ESA (burst mode) ion differential flux spectra, azimuthal (PHI; 0 degrees corresponds to the Earthward direction) angle of ion motion, spacecraft potential (a high-resolution proxy to electron density), parallel component of the ion temperature (red), GSM $V_X$ ion velocity component, DSL $E_Z$ (red), $E_Y$ (green) and $E_X$ (blue) electric field components 3s-long-sliding-window averaged, GSM $B_Z$ (red), $B_Y$ (green) and $B_X$ (blue) magnetic field components.
Figure S2. Time History of Events and Macroscale Interactions during Substorms probe P5 observations on 19 May 2010 between 12:09:30 and 12:15 UT. From top to bottom are shown: joint SST (full mode) and ESA (burst mode) ion differential flux spectra, azimuthal (PHI; 0 degrees corresponds to the Earthward direction) angle of ion motion, spacecraft potential (a high-resolution proxy to electron density), parallel component of the ion temperature (red), GSM $V_X$ ion velocity component, DSL $E_Z$ (red), $E_Y$ (green) and $E_X$ (blue) electric field components 3s-long-sliding-window averaged, GSM $B_Z$ (red), $B_Y$ (green) and $B_X$ (blue) magnetic field components.
Figure S3. (left) Results from 3D PIC simulation of BICI development in the electron (charged) current sheet between \( \Omega_{i0}t = 160 \) and \( \Omega_{i0}t = 250 \) as seen in (from top to bottom) three magnetic field components and in the total magnetic field \((B_x, B_y, B_z)\), X and Y ion velocity components \( V_{ix} \) and \( V_{iy} \), ion density \( N_i \), average ion temperature \( T_i \), nondiagonal ion temperature and ion pressure tensor elements \( T_{ixy} \) and \( P_{ixy} \). In the simulation, the X axis is directed antisunward and the Y axis is dawnward, which is opposite to the GSM X and Y axes. The three curves correspond to the location of three virtual spacecraft at \((x/\rho_{i0},y/\rho_{i0},z/\rho_{i0}) = (10.5, 23.0, 1.5)\) (magenta), at \((x/\rho_{i0},y/\rho_{i0},z/\rho_{i0}) = (12.5, 22.0, 1.5)\) (blue) and at \((x/\rho_{i0},y/\rho_{i0},z/\rho_{i0}) = (13.5, 20.5, 1.5)\) (cyan), i.e. at the same X and Y positions as in the left column of Figure 3 of the manuscript, but in the opposite Z-location. (right) xy configurations of three virtual spacecraft (top) and three THEMIS probes at 12:12UT (bottom).
Figure S4. PIC simulated $E_y$ (a), $E_z$ (b) electric field components. The results are plotted in $x, y$ plane cut at $z/\rho_0 = -1.5$ at time $\Omega i \Omega = 210$. 


Figure S5. From top to bottom are shown Time History of Events and Macroscale Interactions during Substorms probe P4 observations on 19 May 2010 between 12:10:00 and 12:20 UT: joint SST (full mode) and ESA (burst mode) ion differential flux spectra, azimuthal (PHI; 0 degrees corresponds to the Earthward direction) angle of ion velocity, parallel (red) and perpendicular (blue and green) components of the ion temperature, three GSM components of the ion velocity \(V_i\), three diagonal GSM components of the ion pressure tensor \(P_{xx}\) (blue), \(P_{yy}\) (green) and \(P_{zz}\) (red), spacecraft potential (a high-resolution proxy to electron density), and three GSM components of the magnetic field.
Figure S6. Specific initial PIC simulation configuration used in the present study: 2-D $(x,z)$ magnetic field configuration (a), and initial equatorial magnetic field profile $B_{0z}(x,0)$ (b).