Electron dynamics in the reconnection ion diffusion region

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[1] We investigate and compare Cluster observations of electron dynamics in different locations of the ion diffusion region for magnetic reconnection in the Earth’s magnetotail. On the basis of the 2-D reconstructed magnetic field map from Cluster 1 (C1), we pinpoint that the observed Hall field is ~6000 km (~9 ion inertial lengths) away from the magnetic X-point, and reveal that C3 was the one in closest proximity to the X-point at the time when the reconnection jet reversal was simultaneously seen by three spacecraft, namely, C1, C3, and C4. No evidence is found for strong wave emission and energetic electron enhancement near to the X-point, as compared to that within the diffusion region. We find that (1) the Hall current loop is mainly carried by the low-energy, field-aligned counterstreaming electrons; (2) a flat-top distribution in phase space density is a common feature for Hall-related electrons; (3) an enhancement of energetic electrons is observed together with the presence of the flat-top electrons; and (4) electromagnetic wave emission is enhanced within the diffusion region. Two different regions of field-aligned counterstreaming (FC) electrons are identified: one is associated with the Hall current loop (i.e., the electron flow reversal) while another one stays at the edge of the loop. Interestingly, observations show that at the transition between the two FC regions, the waves seem to suppress the energetic electrons but to promote the flat-top electrons.


1. Introduction

[2] Magnetic reconnection is a process of breaking and reconnecting of magnetic field lines in a localized diffusion region. Through reconnection, the magnetic energy is converted into plasma kinetic energy in the form of particle heating and acceleration. Therefore, diffusion region is thought to be a prime region for studying particle acceleration and its physics. Figure 1 illustrates schematically the Hall magnetic field BH and Hall current loop JH for the earthward-directed reconnection jet at the northern separatrix of magnetotail reconnection. The Hall current loop is induced by the decoupling motions of ions and electrons [Sonnerup, 1979; Terasawa, 1983], and is mainly carried by the electrons which velocities are expressed by the purple arrows in Figure 1, where the inflowing and outflowing electrons are antiparallel and parallel to the magnetic field, respectively. According to Ampère’s law, the out-of-plane Hall magnetic field is thus generated by the Hall current loop.

[3] According to the magnetic field orientation, the electron acceleration is categorized into the field-aligned and perpendicular accelerations, for which the acceleration mechanisms are expected to be different. Evidence for electron acceleration up to few keV in the diffusion region has been reported in the Earth’s magnetotail [e.g., Nagai et al., 2001; Asano et al., 2008], showing that the Hall-related electrons are essentially accelerated in the field-aligned direction and its phase space density exhibits a flat-top distribution. Nagai and Fujimoto [2005] found that the Hall current is mainly carried by the low-energy electrons (<5 keV) flowing into the reconnection site. In addition to that, Øieroset et al. [2002] found that in the diffusion region the electron pitch angle distributions show a gradual evolution from field-aligned counterstreaming (<6 keV) to isotropy (>6 keV) with increasing energy. Inside the diffusion region, they also found energetic electrons up to 300 keV which are thought to be accelerated by the inductive electric field at the X-type neutral line. Previous observations of magnetotail reconnection showed that energetic electrons can be generated not only in the X-type diffusion region [e.g., Asano et al., 2008], but also in the magnetic flux pileup...
region [e.g., Imada et al., 2007], and within the magnetic island [e.g., Chen et al., 2008; Retinò et al., 2008].

In the paper, we revisit a reconnection event in the magnetotail seen by Cluster, in which the Hall effects and the X-line crossing are confirmed by Eastwood et al. [2007]. Previous studies by Teh et al. [2011] have shown that the regions of the Hall magnetic field are surrounded by electron-current loops, by use of the steady, 2-D Hall-MHD reconstruction technique [Sonnerup and Teh, 2009]. The purpose of the revisiting is to investigate and compare the electron dynamics in different locations of the ion diffusion region seen by different spacecraft. Further, we examine the possible mechanisms for electron acceleration within the X-type diffusion region. The layout of the paper is as follows.

In section 2, we give an overview of the magnetotail reconnection event and show the Cluster observations of the electron dynamics in different locations of the ion diffusion region. In section 3, we give discussions of the event with the reconstruction results from C1, and conclusions.

2. Cluster Observations of Magnetotail Reconnection

2.1. Overview of the Reconnection Event

[5] Figures 2a–2c show the GSM magnetic field components at 4 s from the FGM instrument [Balogh et al., 2001] for all four Cluster spacecraft, in the time interval between 09:39:00 and 09:48:00 UT, on 22 August 2001. In Figure 2d, the x component of the ion velocity from the Cluster Ion Spectrometry (CIS) instrument [Rème et al., 2001] is shown for C1 and C3 (HIA data) as well as for C4 (CODIF data). Color codes for the spacecraft are: C1, black; C2, red; C3, green; and C4, blue. Vector components are displayed in GSM throughout the paper. For the event, the GSM coordinates (x, y, z) approximately represent the current sheet boundary coordinates (L, M, N), respectively [Eastwood et al., 2007]. Note that the variance coordinates derived from the minimum variance analysis [Sonnerup and Scheible, 1998] are not far from the GSM coordinates [Eastwood et al., 2007; Teh et al., 2011]. During the event, the four Cluster spacecraft, which form a tetrahedron configuration with an average interspacecraft separation of ~2000 km (~3 ion skin depths), were traversing the magnetotail current sheet from northern (Bx > 0) to southern (Bx < 0) hemisphere around (–18.7, –3.4, 1.1) RE in GSM. The first encounter with the current sheet was by C3 at 09:42:19 UT, followed by C2, then by C1, and finally by C4 at 09:46:19 UT. During the traversal, an earthward-directed, high-speed ion flow followed by a tailward flow was simultaneously seen by C1, C3, and C4 at different locations in space, as indicated by the gray dashed line in the bottom panel of Figure 2. The weak tailward flow was suggested to be due to the decrease of the reconnection rate [Eastwood et al., 2007], which is evident because the Bz component becomes smaller (see Figure 2c). But, the reconnection was still ongoing because a strong tailward flow associated with a magnetic island was seen at later time around 09:50 UT and because there was a more or less stable tailward flow for the time interval between the flow reversal around 09:44:28 UT and the strong tailward flow around 09:50 UT (not shown). At the time of the Vx reversal, C3 was at Bx < 0 but the other three spacecraft were at Bx > 0, as shown in Figure 2a. Evidently, a magnetic X-point, located on the tailward side of the spacecraft, moves earthward through the Cluster tetrahedron [Eastwood et al., 2007; Teh et al., 2011]. During

![Diagram](image-url)

**Figure 1.** Schematic of Hall magnetic field BH and Hall current loop JH for the earthward-directed reconnection jet Vout on the northern separatrix of the magnetotail reconnection. The (x, y, z) axes represent the GSM coordinates. The Hall current is carried by the electrons which velocities are shown by the purple arrows. The red dashed line illustrates the current sheet crossing from Northern (Bx > 0) to Southern (Bx < 0) Hemisphere for the virtual spacecraft.

![Figure 2](image-url)

**Figure 2.** Time series plots of (a–c) the GSM magnetic field components at 4 s and (d) the x component of the ion velocity for C1 and C3 from Cluster Ion Spectrometry (CIS)/HIA and for C4 from CODIF. The dashed line denotes the reconnection jet reversal. Color codes for C1, C2, C3, and C4 are black, red, green, and blue, respectively.
the event, the current sheet expands which is evident by comparing the \(B_x\) profiles between C3 and the other three spacecraft [Teh et al., 2011]. We can roughly estimate the half thickness of the current sheet, which is \(1800 \text{ km}\), the relative distance in the \(z\) \text{GSM}\ direction between C3 and C4 at the time when C3 is at the current sheet center but C4 is not within it.

2.2. Electron Observations by C1 and C2

[6] Figure 3 shows the time series measurements of C2 between 09:41:00 and 09:46:00 \text{ UT}. From top to bottom, shown are the \(22 \text{ Hz}\) magnetic field data from the FGM; (b) the \(x\) component of the ion (black) and electron (red) velocity from the Hall-MHD reconstruction and PEACE, respectively; the electron energy-time spectrograms for (c) antiparallel, (d) perpendicular, and (e) parallel directions from PEACE; and (f) the energetic electron fluxes from RAPID; Vector components are shown in \text{GSM}. The blue horizontal lines denote the energies at 1 keV, 3 keV, and 8 keV. The Hall magnetic field region is enclosed by the vertical dashed lines H1 and H3.

For the event, only C2 has available measurements of the electron moment from PEACE with the resolution at 20 s. We note that C4 has similar PEACE spectrograms as C1 but its overall flux is much lower than C1 (not shown), and that the PEACE data from C3 are unfortunately contaminated by the byte-swap data corruption. In the paper, knowledge of the electron velocity for the event is crucial in the analyses of the PEACE data for C1 and C2. With resort to the 2-D Hall-MHD reconstruction, we can estimate the electron velocity for C1 for reference, which is useful in analyzing the PEACE data. The reconstruction can also provide the predicted ion velocity for C2 for reference.

Figure 3. Measurements from Cluster 2 of the magnetotail reconnection in the time interval between 09:41 UT and 09:46 UT on 22 August 2001. From top to bottom, shown are (a) the three components of the \(22 \text{ Hz}\) magnetic field from FGM; (b) the \(x\) component of the ion (black) and electron (red) velocity from the Hall-MHD reconstruction and PEACE, respectively; the electron energy-time spectrograms for (c) antiparallel, (d) perpendicular, and (e) parallel directions from PEACE; and (f) the energetic electron fluxes from RAPID; Vector components are shown in \text{GSM}. The blue horizontal lines denote the energies at 1 keV, 3 keV, and 8 keV. The Hall magnetic field region is enclosed by the vertical dashed lines H1 and H3.

Figure 4. Measurements from Cluster 1 for the same time interval and format as in Figure 3, except that the \(x\) component of the ion (black) and electron (red) velocity are from the CIS/HIA instrument and the 2-D Hall-MHD reconstruction, respectively. The Hall magnetic field region is enclosed by the vertical dashed lines G1 and G3.
The trajectory in Figure 1 illustrates for the crossing from the electron velocity for the event. As the virtual spacecraft is higher than that of the tail lobe. In the tropic around the plasma sheet in which the suprathermal line H3, the low-energy electrons (up to 3 keV) appear iso-

dashed line denotes the energy at 3 keV.

which can be used as a consistency check with the observations seen by the other three spacecraft.

There was no significant $B_x$ guide field in the tail lobe during the reconnection. The positive $B_x$ increase, enclosed by the vertical dashed lines H1 and H3 in Figure 3a and also by the vertical dashed lines G1 and G3 in Figure 4a, is identified as one of the out-of-plane quadrupolar Hall magnetic fields at the northern separatrix for the earthward-directed reconnection jet [Eastwood et al., 2007; Teh et al., 2011], as illustrated in Figure 1. In Figures 3b and 4b, one can see that the Hall magnetic fields correspond to the $V_{ex}$ reversal, in which the negative (positive) $V_{ex}$ indicates the electrons flowing into (out of) the reconnection region in the direction antiparallel (parallel) to the magnetic field. Note that the $V_{ex}$ can be seen as the $x$ component of the parallel electron velocity for the event. As the virtual spacecraft trajectory in Figure 1 illustrates for the crossing from $B_x > 0$ to $B_x < 0$, this negative-then-positive $V_{ex}$ reversal is in agreement with the flow pattern of the Hall electrons, as predicted by the Hall reconnection physics [Sonnerup, 1979]. In the tail lobe, the Alfvén speed is $\sim 1726$ km/s, based on the ion density of 0.1 cm$^{-3}$ and the field strength of 25 nT. Therefore, the electron velocity $V_{ex}$ is super-Alfvénic.

In section 3, by using the 2-D Hall-MHD reconstruction results we will show that the $V_{ex}$ reversal is associated with the loops of the electron streamlines, which are called the Hall current loops [Sonnerup, 1979].

The electron energy-time spectrograms in Figures 3c–3e demonstrate that the electrons are mainly accelerated in the parallel and antiparallel directions within the Hall field region. Also, the field-aligned electron acceleration is accompanied with the enhancement of the energetic electrons as compared to the tail lobe and plasma sheet regions, as shown in Figure 3f. After the time at the vertical dashed line H3, the low-energy electrons (up to 3 keV) appear isotropic around the plasma sheet in which the suprathermal electron flux is higher than that of the tail lobe. In the energy-time spectrograms, a line cutting along the energy at 3 keV shows that two distinct energies of the field-aligned counterstreaming electrons are formed inside the Hall field region, enclosed by the vertical dashed lines H1 and H3. Hereafter we label the two distinct regions of the field-aligned counterstreaming electrons as FC1 and FC2. The FC1 region, enclosed by the dashed lines H1 and H2, is associated with the $V_{ex}$ reversal or the Hall current loop, with the energy between 1 and 3 keV. By contrast, the FC2 region, enclosed by the dashed lines H2 and H3, is located near the edge of the Hall current loop, with the energy between 3 and 8 keV. Evidently, there is a dip of the energetic electron flux at the transition between the FC1 and FC2 regions, in which both regions are accompanied with the higher fluxes of the energetic electrons. In contrast to what C2 observed, more dynamic field-aligned counterstreaming electrons were seen by C1, as shown in Figures 4c–4e, where the Hall field region is enclosed by the dashed lines G1 and G3. With the electron velocity estimated from the reconstruction, we identify the FC1 and FC2 regions for C1, in which the two regions are separated by the dip of the energetic electron flux, the same feature as C2. The results indicate that the FC1 region, which is associated with the Hall current loops, consists of modest ingredients of the electrons with the energy greater than 3 keV and, by contrast, that the FC2 region has more electrons below 3 keV. In section 3, we will discuss more about the dip of the energetic electron flux between the FC1 and FC2 regions.

Figures 5 and 6 show the energy-time cut of the phase space density from PEACE at 0° (blue), 90° (black), and 180° (red) pitch angles for C2 and C1, respectively, at different locations, namely, the FC1 region (Figures 5a, 6a, 5b, and 6b), the FC2 region (Figures 5c, 6c, 5d, and 6d), and the plasma sheet (Figures 5e and 6e). The dashed lines are the one-count level for the three pitch angles and the vertical dashed line denotes the energy at 3 keV. One can find that the flat-top distribution is established for the electrons within
the FC1 and FC2 regions, for example, as shown in Figures 5b, 5c, 6a, and 6c. For C2, within the FC1 region as well as the plasma sheet, the phase space density for the field-aligned pitch angles drops sharply for the energy greater than 3 keV. But, it shows an increase within the FC2 region instead, as shown in Figure 5d. This result reveals that the electrons exhibit further accelerations in the field-aligned directions.

3. Discussions and Conclusions

[11] Figure 7 shows the 2-D Hall-MHD reconstruction results from C1 for the time interval between 09:39 and 09:48 UT. The reconstruction assumes that the field and plasma structures are governed by the steady, two-dimensional, ideal Hall-MHD equations in which the electron pressure gradient and the resistive term are omitted in the generalized Ohm’s law [Sonnerup and Teh, 2009]. The upper panel shows the magnetic field line map, while the bottom panel shows the ion streamlines (in gray), together with the electron streamlines (in black) around the Hall field region. The color code is the out-of-plane magnetic field component \( B_z' \). Note that the \( z' \) axis is the invariant axis along which the variation is negligible. In the bottom panel, the white arrows at \( y' = 0 \) are the reconstructed electron velocities along the C1 spacecraft trajectory, and those velocities are seen in the moving frame with the structure. In the previous studies, Teh et al. [2011] have systematically verified the reconstruction results by optimizing the reconstruction axes \( (x', y', z') \) and the moving frame velocity \( V_0 \) in GSM: \( x' = (-0.896, 0.016, -0.445); y' = (-0.444, 0.014, 0.896); z' = (0.021, 1.000, -0.006); \) and \( V_0 = (29.4, -2.2, 5.4) \) km/s. The red plus symbol denotes the magnetic X-point and the pink curve is the contour of \( B_{x'} = 0 \) representing the current sheet center. In Figure 7 (top) the white arrows denote the magnetic field directions on both sides of the current sheet. In Figure 7 (bottom) the white arrows at \( y' = 0 \) are the reconstructed electron velocities along the C1 spacecraft trajectory, crossing the current sheet from left to right. The pink arrows represent the reconstructed ion flow velocities along the C3 and C4 spacecraft trajectory. The white tetrahedron configuration denotes the spacecraft locations at the time when the reconnection jet reversal was seen. The cyan and blue bars denote the FC1 and FC2 regions, respectively, at C1 and C2. Tailward is to right and northward is to the top.

![Figure 6](image-url)  
**Figure 6.** One-dimensional cut of the C1 phase space density from PEACE. The format is the same as in Figure 5.

![Figure 7](image-url)  
**Figure 7.** Ideal Hall-MHD reconstruction results from C1. (top) Map of the magnetic field lines with the out-of-plane magnetic field \( B_z' \) in color. (bottom) Map of the ion (gray) and electron (white) streamlines with the \( B_z' \) in color. The reconstruction axes \( (x', y', z') \) and the moving frame velocity \( V_0 \) are in GSM: \( x' = (-0.896, 0.016, -0.445); y' = (-0.444, 0.014, 0.896); z' = (0.021, 1.000, -0.006); \) and \( V_0 = (29.4, -2.2, 5.4) \) km/s. The red plus symbol denotes the magnetic X-point and the pink curve is the contour of \( B_{x'} = 0 \) representing the current sheet center. In Figure 7 (top) the white arrows denote the magnetic field directions on both sides of the current sheet. In Figure 7 (bottom) the white arrows at \( y' = 0 \) are the reconstructed electron velocities along the C1 spacecraft trajectory, crossing the current sheet from left to right. The pink arrows represent the reconstructed ion flow velocities along the C3 and C4 spacecraft trajectory. The white tetrahedron configuration denotes the spacecraft locations at the time when the reconnection jet reversal was seen. The cyan and blue bars denote the FC1 and FC2 regions, respectively, at C1 and C2. Tailward is to right and northward is to the top.
event, taken from the reconstruction for quasi-equilibrium in the fixed moving frame, since there are time-dependent effects resulting from the current sheet expansion and its wavy motion [Teh et al., 2011]. Such time-aliased effect is present in the ion and electron streamlines, for example, in Figure 7 the outgoing electron flow in FC1 region is somewhat deviated outside of the separatrix.

[12] According to the field line map, we estimate the distance between the magnetic X-point, denoted by the red plus symbol, and the Hall magnetic field region, which is \( \sim 6000 \text{ km} \) (\( \sim 9 \) ion inertial lengths). In the map, the white tetrahedron denotes the spacecraft locations at the time when the reconnection jet reversal was seen at C1, and the pink curve represents the current sheet center where \( B_x = 0 \). The map shows that C3 is on the right-hand side of the current sheet, while the other three spacecraft are on the opposite side. This result agrees with the observation that C1, C2, and C4 are at \( B_x > 0 \) while C3 is at \( B_x < 0 \), as shown in Figure 2a. Moreover, the map reveals that C3 was the one in closest proximity to the X-point at the time when the flow reversal was simultaneously seen by C1, C3, and C4. Note that in the map, northward is to the top (\( y' > 0 \)), and tailward is to the right (\( x' > 0 \)). Additionally, Figure 7 shows that (1) the current sheet is curvy and slanted; (2) the 2-D magnetic field and ion flow configurations near the reconnection site are much more complicated than a simple X-line configuration of a steady reconnection in a planar current sheet; and (3) a tailward flow is simultaneously observed by the three spacecraft (C1, C3, and C4) after the flow reversal. We point out that the map cannot be sufficient to describe the C3 flow behavior before the flow reversal. This is partly because of the time-dependent effects on the C1 reconstruction results as mentioned previously.

[13] Figure 8 shows from top to bottom: the \( B_z \) field component for all four spacecraft (Figure 8a); the ion velocity component \( V_x \) for C1, C3, and C4 (Figure 8b); and the frequency-time spectrograms from STAFF [Cornilleau-Wehrlin et al., 2003] for the magnetic field for all four spacecraft, in order of the current sheet crossing. The magenta dashed line denotes the \( V_x \) reversal; the three gray lines denote the fast flow onset for C1, C3, and C4; and the green dashed line denotes the Hall-field encounter for C4. We see that no indication is found for strong wave emission at the time of the \( V_x \) reversal for C3. But, as compared to the tail lobe and plasma sheet regions, the wave emissions are strongly enhanced within the Hall field regions seen by C3 and also by the other three spacecraft. We point out that C3, which is the spacecraft closest to the X-point, observed a decrease in the energetic electron flux at the time of the \( V_x \) reversal (not shown). Similar results have also been obtained by Fujimoto et al. [2011] and Nagai et al. [2011] when studying a reconnection event in the magnetotail seen by Geotail. In addition, Figure 8 shows that for C1 and C3 the wave onset is well correlated not only with the fast flow onset, but also with the Hall-field encounter. For C4, the wave onset is prior to the fast flow onset but is still well correlated with the Hall-field encounter. These results demonstrate that the wave enhancement is attributed to spatial effects. Note that the wave frequency falls within the lower-hybrid frequency range.

[14] Because the suprathermal electrons are seen inside the diffusion region together with the presence of the flat-top electrons, we do not consider the two-step acceleration mechanism proposed by Hoshino et al. [2001] for which the suprathermal electrons are accelerated in the pileup region. During the current sheet crossing, the observations show that the slope of the \( B_x \) field profile first seen by C3 is steeper than that observed by the other three spacecraft at the later different times (see Figure 2a). In other words, the current sheet expands during the event. As a result, this particular event suggests that the electron acceleration does not occur under current sheet thinning conditions [e.g., Imada et al., 2007, 2011]. In addition to the reconnection electric field, there are possible mechanisms that have been proven for electron acceleration near the X-type diffusion region, for example, (1) formation of an acceleration potential [Egedal et al., 2010a, 2010b]; (2) surfing acceleration [Hoshino, 2005]; and (3) wave particle interaction with obliquely propagating lower-hybrid waves [Shinohara et al., 1998]. Yet we are not sure which mechanism finally plays the key role.
role in the electron acceleration for this event. Nevertheless, the condition of this event seems to favor the third mechanism because we have seen the lower-hybrid wave enhancement within the diffusion region.

[15] In the present study, we have identified two FC regions within the diffusion region. The FC1 region, which is associated with the Hall current loop, has been identified by the previous studies [e.g., Nagai et al., 2001; Nagai and Fujimoto, 2005]. What is the FC2 region? Yet we do not have a clear answer for that, but we conjecture that the FC2 region could be the consequence that the electrons are heated through the resonance with the obliquely propagating lower-hybrid waves [Shinohara et al., 1998].

[16] Figure 9 shows for C1 and C2 the observations of (Figure 9a) the energetic electron fluxes, (Figures 9b and 9c) the PEACE spectrograms for antiparallel and parallel directions, and (Figure 9d) the STAFF spectrogram for electric field. One can find that (1) the overall wave activity in the FC1 region is stronger than the FC2 region; (2) in the FC2 region the wave emission for C1 is much declined than C2. The figure also reveals that, at the transition between FC1 and FC2 regions, as denoted by the dashed lines H2 and G2, the wave emission is enhanced together with a decrease of the energetic electron flux, but with an increase of the energy flux of the flat-top electron. This relationship between the wave and the flat-top and energetic electrons is, however, not unambiguously evident at the other locations. For instance, for C2 the energetic electron flux decreases with a weak wave emission around 09:43 UT; for C1 and C2 the wave emission increases with no increase of the energy flux of the flat-top electron around 09:42 UT. Yet, it is unclear to us why the waves behave quite differently at different locations of the diffusion region. The result seems to suggest that there are different mechanisms responsible for the electron acceleration and heating.

[17] In conclusion, we have investigated and compared the electron dynamics in different locations of the Hall field region seen by different spacecraft. From the reconstruction map, we pinpoint that the observed Hall field is ~6000 km (~9 ion inertial lengths) away from the X-point, and reveal that no enhancements of the energetic electron and the wave emission are found near to the X-point, consistent with the result by Fujimoto et al. [2011] and Nagai et al. [2011]. In the study, the flat-top distribution in the phase space density is found to be a common feature for the Hall-related electrons, a result that had been reported by Asano et al. [2008]. According to the energy-time spectrograms from C2, the Hall current is mainly carried by the low-energy (1–3 keV), field-aligned counterstreaming electrons, but sufficiently by the inflowing ones. This result is consistent with the previous finding by Nagai and Fujimoto [2005]. Interestingly, we find another field-aligned counterstreaming electron, with the energy between 3 and 8 keV, which is formed near the edge of the Hall current loop. Such structure of the flat-top electrons seen by C2 is, however, less evident in C1. Instead, more dynamic field-aligned counterstreaming electrons were seen by C1, in which the high-energy electrons (3–8 keV) are less obviously separated from the low-energy ones. Within the diffusion region, the energetic electron is observed together with the presence of the flat-top electrons, and the electromagnetic wave emission is enhanced. Finally, it is interesting to note that at the transition between the FC1 and FC2 regions the waves seem to suppress the suprathermal electrons but to promote the flat-top electrons.
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