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Key Points:

- Electron acceleration in magnetic reconnection is a multistage process
- Electrons can be accelerated successively in different regions
- The multistage process is an essential ingredient to produce energetic electron

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In situ observations of multistage electron acceleration driven by magnetic reconnection

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Abstract With observations of magnetic reconnection and the related bursty bulk flow (BBF) in the magnetotail by Time History of Events and Macroscale Interactions during Substorms mission, we investigate the process of the multistage acceleration of electrons in magnetotail reconnection events, which can be divided into three distinct stages: (1) first, electrons are accelerated in the vicinity of the X line where the electron temperature can be significantly raised while the energetic electron flux with the energy larger than tens of keV has no obvious enhancement. (2) Second, electrons suffer the nonadiabatic acceleration in the pileup region of magnetic reconnection, which results in the obvious enhancement of the energetic electron flux and the small increase of the electron temperature in the earthward flow. (3) At last, the energetic electron flux can be further raised in the BBFs due to adiabatic acceleration mechanisms. Our study indicates that low-energy electrons can be accelerated to a high energy with a multistage process in magnetic reconnection events, which ranges from the vicinity of the X line to the BBFs.

1. Introduction

Magnetic reconnection provides an effective mechanism for the conversion of magnetic energy into plasma kinetic energy [*Drake and Shay*, 2007; *Lu et al.*, 2013; *Yamada et al.*, 2014]. The production of energetic electrons is one of the fundamental signatures in magnetic reconnection [*Baker and Stone*, 1977; *Øieroset et al.*, 2002; *Imada et al.*, 2005; *Chen et al.*, 2008; *Wang et al.*, 2010a]. Previous research had focused electron acceleration on the region in the vicinity of X line, where electrons are energized by the reconnection electric field [*Hoshino et al.*, 2001a; *Drake et al.*, 2005; *Fu et al.*, 2006; *Pritchett*, 2006; *Wan et al.*, 2008; *Huang et al.*, 2010; *Egedal et al.*, 2010, 2012]. The efficiency of electron acceleration during magnetic reconnection is found to be enhanced when a guide field exists in the current sheet, because the electrons can stay a longer time in the diffusion region due to the electron gyromotion [*Fu et al.*, 2006; *Pritchett*, 2006].

Øieroset et al. [2002] showed the first in situ evidence for the existence of energetic electrons with energies up to 300 keV inside the diffusion region of a magnetotail reconnection event observed by the Wind spacecraft, which suggested the occurrence of the significant electron energization near the reconnection site. Ever since then, more and more in situ evidences of electron acceleration near the reconnection site have been found by in situ observations in the magnetotail [*Wang et al.*, 2010a, 2010b; *Huang et al.*, 2012]. Besides the vicinity of X line, electrons have been shown to be accelerated in other regions associated with magnetic reconnection. With particle-in-cell (PIC) simulations, *Fu et al.* [2006] and *Drake et al.* [2006] proposed independently that electrons can be accelerated in a contracting magnetic island. Cluster observations of magnetic reconnection in the magnetotail have also found that [*Chen et al.*, 2008; *Wang et al.*, 2010a, 2010b; *Huang et al.*, 2012] the peak of energetic electron fluxes is inside magnetic islands, which indicated the important role of the formation and dynamics of magnetic islands in electron acceleration.

With PIC simulations *Hoshino et al.* [2001a] demonstrated that during magnetic reconnection the accelerated electrons in the vicinity of X line could be further energized after they enter the pileup region, where the magnetic field is piled up when the plasma away from the X line is decelerated. The process of electron acceleration in the pileup region is usually nonadiabatic, because here the electron gyroradius is comparable to the curvature radius of the magnetic field lines and the electron motion is then stochastic. Therefore, *Hoshino et al.* [2001a] proposed that the process of electron acceleration in magnetic reconnection could suffer a two-stage acceleration: first, in the vicinity of the X line and then in the pileup region. In a magnetotail reconnection event observed by Cluster, *Imada et al.* [2007] found that the enhancement of the energetic electron flux in the outflow region is associated with large B_z, and their results indicated that electrons can be accelerated by a nonadiabatic process in the pileup region.

Recently, dipolarization fronts (DFs) in the Earth's magnetotail driven by magnetic reconnection have also been considered to be one another site to accelerate electrons with energies up to hundreds of keV [*Zhou et al.*, 2009; *Runov et al.*, 2011; *Ashour-Abdalla et al.*, 2011; *Pan et al.*, 2012; *Birn et al.*, 2013, 2014; *Huang et al.*, 2015]. By using Time History of Events and Macroscale Interactions during Substorms (THEMIS) data, *Runov et al.* [2011] indicated that the DFs are always accompanied with large variations of the energetic electron (30–200 keV) flux and electron temperature. Betatron and Fermi accelerations are invoked to explain the energetic electrons observed in dipolarization fronts associated with magnetotail reconnection [*Fu et al.*, 2011, 2013; *Pan et al.*, 2012]. With the THEMIS data, a statistical study revealed that the energetic electron flux behind the earthward moving dipolarization fronts increases due to adiabatic acceleration processes [*Wu et al.*, 2013]. Therefore, in magnetic reconnection electrons may be accelerated in these regions: the vicinity of X line, the pileup region, and DFs driven by reconnection. The energetic electrons should suffer a multistage acceleration process. In this paper, we fortunately find three reconnection events in the magnetotail observed by THEMIS, where the reconnection region observed by THB and DF in the bursty bulk flow (BBF) by other spacecraft was in the same flow channel. The DFs in the BBF detected by other spacecraft can be thought to be driven by the reconnection event in the same flow channel, which gives us a chance to in situ study the whole process of electron acceleration ranging from the vicinity of the X line, the pileup region to BBF. We reveal the multistage process of electron acceleration from the thermal energy in the vicinity of the X line to hundreds of keV in the DF, and the characteristics of each acceleration stage are discussed in detail. Such a multistage process is considered to be an essential ingredient for the generation of energetic electrons.

2. Data Set

In this paper, the geocentric solar magnetospheric (GSM) coordinate system is used unless noted otherwise. Between January and April of the 2 years 2008 and 2009 the apogee of the THEMIS mission was in the magnetotail. This mission has five identical spacecraft aligned along the magnetotail. And each THEMIS spacecraft carries identical instruments [*Angelopoulos*, 2008]. The configuration of THEMIS supply us an opportunity to simultaneously observe magnetic reconnection and the related bursty bulk flows (BBFs) far away from the X line. By analyzing such events, we can study the whole process of electron acceleration from the vicinity of the X line to the earthward propagated flows. In this paper, the earthward propagated flows near the reconnection site are called "earthward flow," while the earthward propagated flows far away the reconnection site are named "BBF."

In this study, we use the 4 Hz resolution and 128 Hz resolution magnetic field data from the fluxgate magnetometers (FGMs) [*Auster et al.*, 2008]. The electrostatic analyzer (ESA) [*McFadden et al.*, 2008] can provide ion and electron distribution functions in the less than 30 keV energy range with a time resolution of 3 s. The Solid State Telescope (SST) [*Angelopoulos*, 2008] detects high-energy (greater than 30 keV) ion and electron fluxes with the same time resolution as ESA. The electron/ion temperature, plasma density, and bulk flow velocity are obtained by the measurements of ESA in this study. In the magnetotail, the energy of the thermal electrons is usually less than several keV, which can be fully covered by the measurements of ESA. The contributions of energetic electrons obtained by SST to electron temperature are always negligible.

3. Results

3.1. Reconnection Event and the Related Bursty Bulk Flow

During the time interval of 04:50–05:10 UT on 26 February 2008, the THEMIS probes THB and THC were in the plasma sheet, located at about [−21.3, 3.8, −2.8] R_E and [−17.4, 4.4, −3.1] R_E in geocentric solar magnetospheric coordinates, respectively. Figure 1 shows an overview of the magnetic field and plasma data during this time interval which were observed by THB. THB observed a tailward high-speed flow followed by an earthward flow, and the reversal happened at about 05:00:00 UT (Figure 1c). At almost the same time, B_z changed its sign from negative to positive (Figure 1b). During most of the time interval, the observed B_x

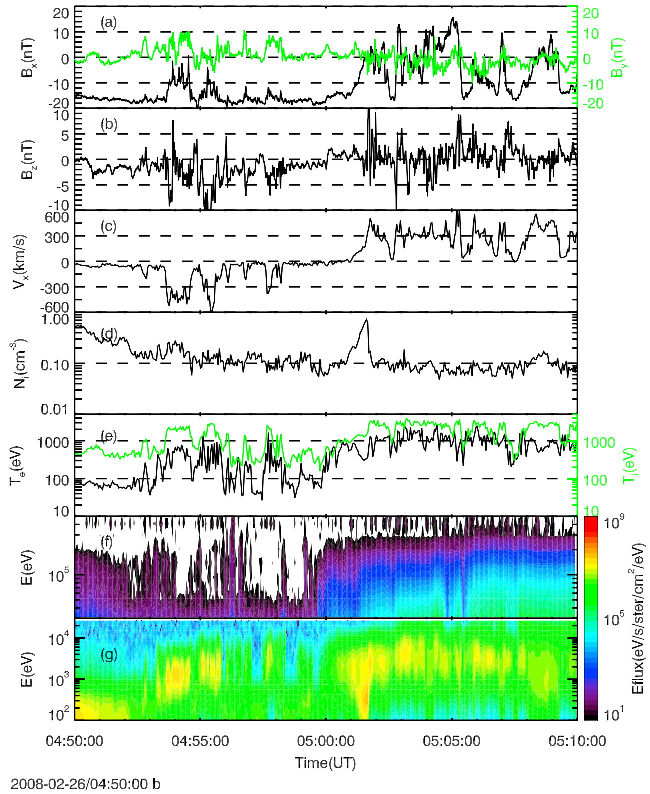

Figure 1. The magnetic field and particle data obtained by THB between 04:50 and 05:10 UT on 26 February 2008. There are (a) B_x (black line) and B_y (green line), (b) B_z, (c) the x component of ion flow velocity v_x, (d) ion density n_i, (e) electron temperature T_e (black line) and ion temperature T_i (green line), (f) electron differential energy flux with the energy from 30 keV to 500 keV which is obtained by SST, and (g) electron differential energy flux with the energy from 100 eV to 30 keV which is obtained by ESA.

was negative, which indicated that THB was mainly in the southern part of the plasma sheet (Figure 1a). With the reversal of B_z from negative to positive, B_y changed value from positive to negative, which is in agreement with the prediction of the quadrupolar out-of-plane Hall magnetic field configuration [*Øieroset et al.*, 2001]. All these characteristics demonstrate that THB passed through the reconnection site of an antiparallel magnetic reconnection event from the tailward to the earthward side of the X line [*Angelopoulos et al.*, 2008]. However, we should note that the strong magnetic fluctuation observed by THB in this event and the quadrupolar out-of-plane Hall magnetic field configuration sometimes do not fit the theoretical prediction well. *Vörös et al.* [2009] pointed out that the kink mode can be generated in the outflow region in this event, which could be the reason of the complicated current system and strong magnetic fluctuation. The ion density and electron/ion temperature are shown in Figures 1d and 1e, respectively. In the magnetotail, the electron density is nearly the same with the ion density. In this event, the tailward flow is mainly observed from 04:53:20 UT to 04:58:20 UT, and the earthward flow is mainly observed from 05:01:00 UT to 05:10:00 UT. Most of time, the tailward flow is always denser and colder than the earthward flow. There is one exception which happens around 05:01:30 UT. The electron flux spectrum in Figure 1g shows that a cold component of electrons with energy about 0.4 keV is mixed with the hotter earthward flow with energy about 2 keV (a cold component of ions is also observed at the same time). This leads to an abnormal high density.

About 2 min after THB detected the reversal of the high-speed flow, a bursty bulk flow (BBF) with a velocity up to ~600 km/s was observed by THC. Figure 2 shows the magnetic field components, the x component of bulk velocity, the particle density, the electron energy flux spectrum in this BBF. This BBF lasts from about 05:01:40 UT to 05:10:00 UT. In general, the width of a high-speed flow is about 2–3 R_E [*Nakamura et al.*, 2004], and here the BBF observed by THC was in the same flow channel with the earthward flow detected by THB. Therefore, we infer that the BBF is the result of the reconnection event observed by THB. At the leading edge of the BBF, a dipolarization front with a sharp jump of B_z was detected at about 05:02:11 UT (Figure 2b). Besides, THC also observed other DFs with sharp jump of B_z in this BBF, such as the DF around 05:03:30 UT and another one around 05:04:20 UT. In this study, we try to study electron acceleration process. For this goal, we focused on the time interval from the first DF detected from 05:02:11 UT to 05:10:00 UT. During this interval, the data of the thermal and energetic electrons are available for most of time.

3.2. Survey of the Thermal and Energetic Electrons

The process of electron acceleration in a reconnection event can be investigated with the observations by THB and THC. For this purpose, the electron temperature T_e, the electron differential energy flux with the energy 31 keV (if not stated clearly, the electron flux in this paper means the electron differential energy flux with the energy 31 keV), and the power law index of the electron differential energy flux over the energy

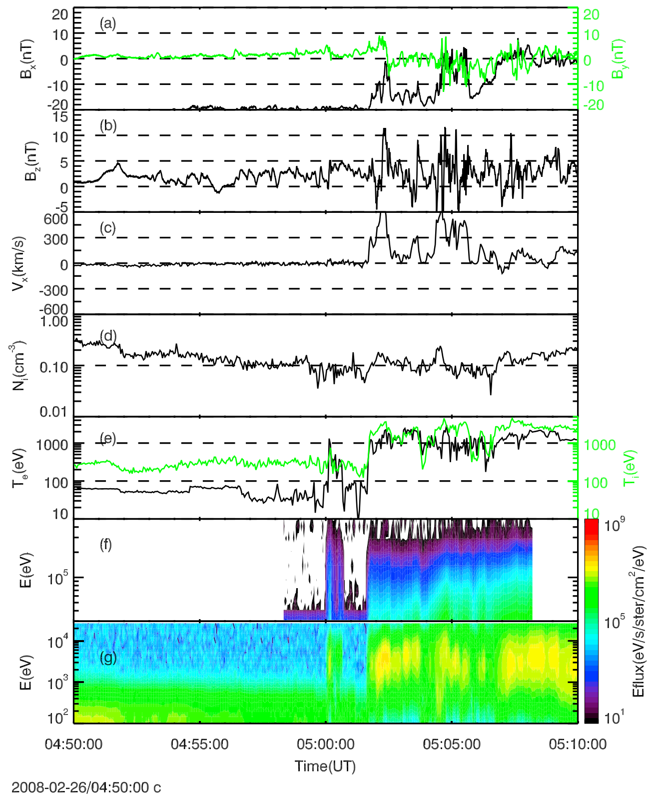

Figure 2. The magnetic field and particle data obtained THC between 04:50 and 05:10 UT on 26 February 2008. The format is the same as in Figure 1.

range [30 keV, 200 keV] are analyzed. The power law index is calculated by using a least squares fit to the differential flux as a function of energy on a log-log scale. The electron flux and power law index are used to represent the variation of the energetic electron flux over the energy range [30 keV, 200 keV]. This analysis is carried out in (v_x, B_x) space. $|B_x|$ can represent the position relative to the center of the current sheet, and v_x is related to the flow strength and direction. Figure 3 shows the distributions of the electron temperature T_e, the electron flux, and the power law index near the reconnection site and in the BBF. Near the reconnection site we focused on the distributions in the tailward flows (a1, a2, and a3) and earthward flows (b1,b2, and b3), while in the BBF we are only concerned with the time interval starting with the appearance of the DF at 05:02:11 UT up until 05:10:00 UT (c1, c2, and c3). And the median values of these parameters in different regions are listed in Table 1.

In this event, both the electron temperature and energetic electron flux have their smallest values in the lobe region which is identified by $|B_x| \geq 19$ nT and $|v_x| \sim 0$ km/s. In the lobe region, T_e is about tens of eV and the electron flux is always on the level of instrument noise. Figure 3a1 shows that in the tailward flow the electron temperature T_e is always hundreds of eV, sometimes can even reach 1.6 keV. The median value of $\log_{10} T_e$ is about 1.9 in the lobe and 2.7 in the tailward flow, respectively. It means that T_e increases about an order of magnitude from the lobe to the tailward flow. Compared with the tailward flow, Figure 3b1 shows that the earthward flow has a slightly higher electron temperature. The values of T_e in the earthward flow sometimes are higher than 2.5 keV. The results of Figures 3a1 and 3b1 indicate that electrons heating mainly occurred from the lobe to the high-speed outflow near the reconnection site. One possibility is that electrons are heated in the vicinity of X line. *Hoshino et al.* [2001b] pointed out that the reconnection electric field could be responsible for the strong electron heating. Moreover, they found that in the plasma sheet boundary layer the thermal electron distributions consist of a cold electron beam toward the X line and a hot electron beam away from the X line. Such distribution could generate instabilities and waves. And these waves can also play an important role in the electron heating process. We also found this kind of electron distribution in our events. In Figure 1g we can also find that the distribution consisted of a cold component and a hot component around the time 05:01:40 UT. Such distribution could generate the bump-on-tail instability. Previous works have shown that this instability could generate electrostatic waves which could also heat electrons in magnetic reconnection [*Huang et al.*, 2014]. Additionally, the higher T_e in the earthward flow indicates that there is another heating process which only happened in the earthward flow. Figure 3c1 shows the electron temperature in the BBF. The median value of T_e in the BBF is at the same level as in the earthward flow near the reconnection site (see Table 1). It seems that in the event there is no obvious heating during the earthward propagation of high-speed flow that originated from magnetic reconnection.

The electron flux and power law index can provide information about the energization of electrons. As shown in Figure 3a2, the electron flux has no obvious change with the variations of B_x and v_x in the tailward flow near the reconnection site. Compared with the electron flux in the lobe, we cannot find obvious enhancement of

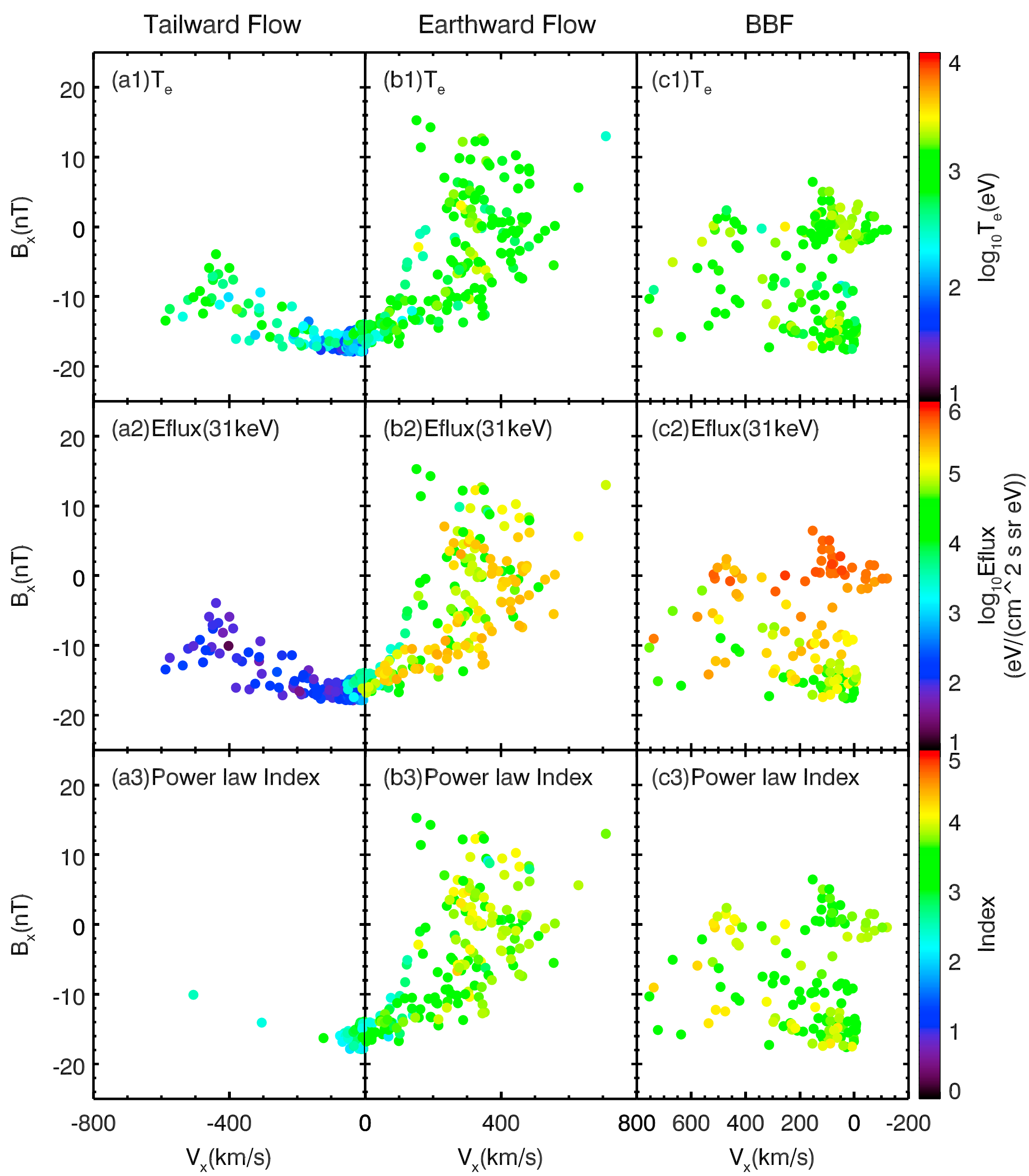

Figure 3. The distributions of (a1) electron temperature T_e, (a2) electron differential energy flux with the energy 31 keV, and (a3) the value of the power law index of electron differential energy flux in the energy range [30 keV, 200 keV] in (v_x,B_x) space in the tailward flow, which are observed by THB. (b1, b2, and b3) The corresponding distributions in the earthward flow near the reconnection site, which are also observed by THB. (c1, c2, and c3) The corresponding distributions in the BBF (from the region just behind the DF to the end of BBF), which are observed by THC.

Table 1. The Median Values of the Electron Temperature, the Electron Differential Energy Flux With the Energy 31 keV, and the Power Law Index at the Energy Range [30 keV, 200 keV] in the Lobe, Diffusion Region (Include the Tailward Flow and Earthward Flow), and BBF

		Diffusion Region			
	Lobe	Tailward Flow	Pileup Region	The Part of Earthward Flow After 05:06:00 UT	BBF
$\log_{10}T_e$ (eV)	1.9	2.7	3.1	3.0	3.1
$\log_{10}Eflux$ (eV/cm^2 s sr eV)	1.8	1.9	4.4	5.2	5.4
Index	/	/	3.4	3.6	3.6

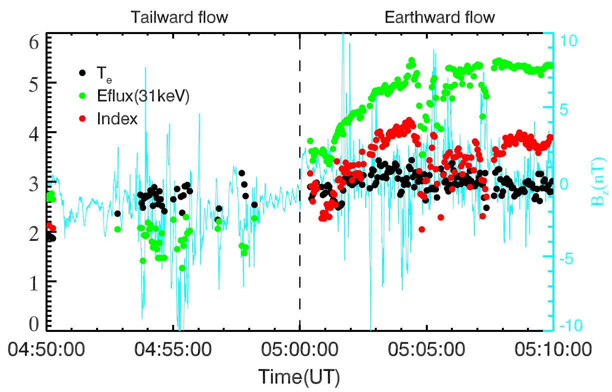

Figure 4. The electron temperature T_e(black points), electron differential energy flux with the energy 31 keV (green points), and the power law index (red points). The cyan line is B_z. The dashed line is the reversal time of v_x and B_z. The unit of T_e is eV, and energy flux is in unit of eV/(cm^2 s sr eV).

the electron flux (31 keV) in the tailward flow. In Figure 3b2, there is also no obvious relationship between the electron flux and B_x or v_x in the earthward flow near the reconnection site. However, the earthward flow contains more energetic electrons than the tailward flow. This has also been observed in previous observations [*Imada et al.*, 2005]. Because the electron density in the tailward flow is a bit larger than that in the earthward flow (see Figure 1d), such distribution is not due to the variations of density. An effective acceleration process should happen in the earthward flow. Figure 3c2 shows the electron flux in the BBF. Different with the distributions observed in the high-speed flow near the reconnection site, in the BBF the electron flux is dependent on B_x, and it increases when approaching the center of the current sheet. The median values of the electron flux $\log_{10}Eflux$ (eV/cm^2/s/sr/eV) are 5.7 for $|B_x| < 5$ nT, 5.2 for $5 < |B_x| < 10$ nT, and 5.0 for $10 < |B_x| < 15$ nT, respectively. The electron flux in the BBF is a bit larger than that in the earthward flow near the reconnection site. The median value of power law indices in the BBF is 3.6, and it is also 3.6 in the earthward flow. Besides, most of time the power law indices are in the narrow range (3.0, 4.0) in these two regions. So the power law index of the energetic electrons in the BBF is almost the same as that in the earthward flow near the X line. In the earthward flow and the BBF, waves are always observed. However, the power law indices show that the adiabatic acceleration during the earthward propagation of the high-speed flow seems to be more important. We also find that the enhancement of the electron flux occurs obviously in the center of the current sheet during the earthward transport. Therefore, this acceleration process could be more effective in the center of current sheet. By investigating the pitch angle distribution of the energetic electrons (>30 keV) in the BBF (not shown), we find that the energetic electrons have pancake distributions in the region where the flow speed rises, while they have cigar distributions in the region where the flow speed falls. This suggests that the acceleration mechanisms in the BBF could include both betatron and Fermi accelerations.

The electron acceleration near the reconnection site can be analyzed in detail by studying the variations of electron temperature and flux in the outflow region when flows move away from the X line, and these variations in the region $|B_x| \leq 15$ nT are shown in Figure 4. The units of electron temperature and energy flux are the same with Figure 3, and the values are the results of raising a base-10 logarithm. The electron temperature (dark points) and electron flux (green points) in the tailward flow have no obvious increase when the flow propagates away from the X line. However, in the earthward flow, energetic electron flux (green points) begins to rapidly increase at about 05:01:30 UT, where a sharp jump of B_z is detected. This increase lasts about 3 min, and the power law index is also continuously increasing during this time period. Therefore, the electrons suffer from an obvious acceleration in the region with the pileup of the magnetic field. The pitch angles of the electrons (>30 keV) in this region always have an isotropic distribution (not shown) during this 3 min, and the acceleration is therefore nonadiabatic. We can reasonably assume that the curvature radii of the magnetic field lines are comparable to the half width of current sheet which is about one ion inertia length [*Nakamura et al.*, 2002; *Imada et al.*, 2011]. The gyroradii of energetic electrons with energy 31 keV can reach about 1000 km around 05:01:37 UT, where the sharp jump of B_z is detected. The ion inertia length is about 700 km in this region. It means that the gyroradii are comparable to the curvature radii of the magnetic field lines. The observational features of this acceleration process are consistent with the theoretical prediction in the pileup region: because the curvature radii of the magnetic field lines are comparable to the gyroradii of the energetic electrons, the energetic electrons can be accelerated by ∇B drift and/or curvature drift under nonadiabatic motion with effective pitch angle scattering [*Imada et al.*, 2007; *Hoshino et al.*, 2001a; *Huang et al.*, 2010]. This nonadiabatic

Table 2. The Magnetic Reconnection Events[a]

Event	Date	Time Interval	Magnetic Reconnection	BBFs
1	26/02/2008	03:58:00–04:10:00	THB	THD/THE
2	27/02/2009	02:25:00–03:05:00	THB	THC/THD

[a]Given are the event number, the data, the time interval, the spacecraft observed a magnetic reconnection, and the spacecraft observed the related BBFs.

acceleration, which lasts for 3 min, causes the enhancement of electron flux by a factor of ~100. The electron temperature (dark points) is also slightly increased in this process. It could be a reason why the earthward flow has higher T_e than the tailward flow. We should note that in this event both THB and THC observed strong magnetic fluctuations which indicated strong wave activity. In the pileup region of this event the electron gyrofrequency is in the range from 10 to 300 Hz. The plasma waves with the frequencies in this range can scatter energetic electrons and interacted with electrons. The wave activities could also play a role in the electron acceleration process.

After about 05:04:11 UT, a bipolar B_z can be observed and such a structure may be associated with a magnetic island. The structure lasts for ~80 s, and the energetic electron flux inside it is quite low. At 05:06:00 UT, the electron temperature, electron flux, and index are returning to the level in the pileup region. After this time (05:06:00 UT), the electron temperature almost does not change, while the electron flux begins to grow slowly and the power law index is nearly constant. These characteristics indicate that the acceleration after the time 05:06:00 UT is an adiabatic process. Therefore, in the earthward flow, the electron flux increased as the flow moves far away from the X line. Energetic electrons can be first accelerated by a nonadiabatic mechanism in the pileup region and then accelerated by some adiabatic acceleration processes in the earthward moving flows. However, the electron temperature increased mainly in the pileup region. In the whole tailward flow, the electron temperature and energetic electron flux are almost on the same level. The acceleration that occurred in the pileup region does not happen in the tailward flow, which makes both the temperature and the electron flux in the tailward flow lower than that in the earthward flow.

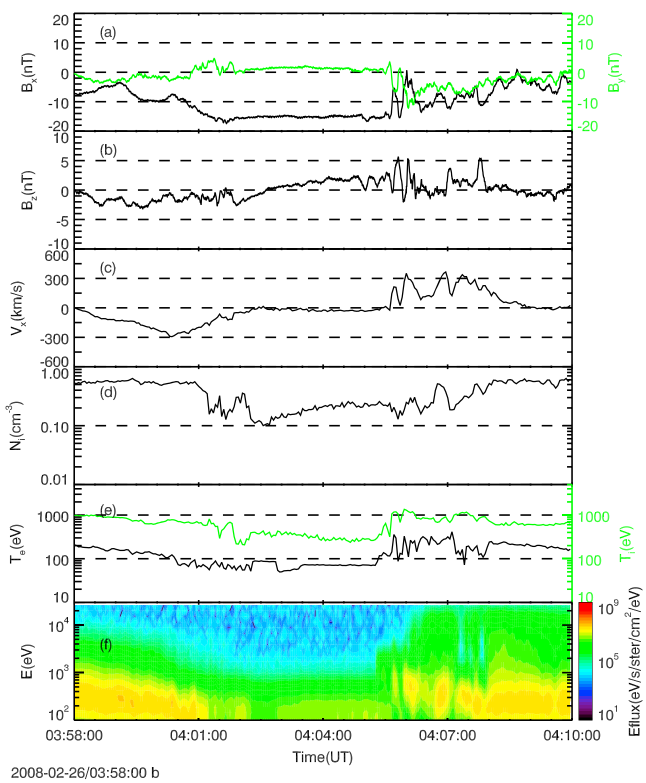

Figure 5. The magnetic field and particle data obtained by THB between 03:58 and 04:10 UT on 26 February 2008. There are (a) B_x (black line) and B_y (green line), (b) B_z, (c) the x component of ion flow velocity v_x, (d) ion density n_i, (e) electron temperature T_e (black line) and ion temperature T_i (green line), and (f) electron differential energy flux with the energy from 100 eV to 30 keV which is obtained by ESA.

Our observations show that there are three different acceleration regions in the magnetic reconnection: the vicinity of X line, pileup region, and the region behind the DF. In our events there are no direct observations of temperature and energetic electron flux enhancements in the vicinity of X line, but we can infer that there is an acceleration process by the comparison between the lobe and the high-speed flows (both the tailward and earthward flows) near the reconnection site. Electrons can get effective acceleration in these three regions step by step, which leads to the high energetic electrons observed in this event.

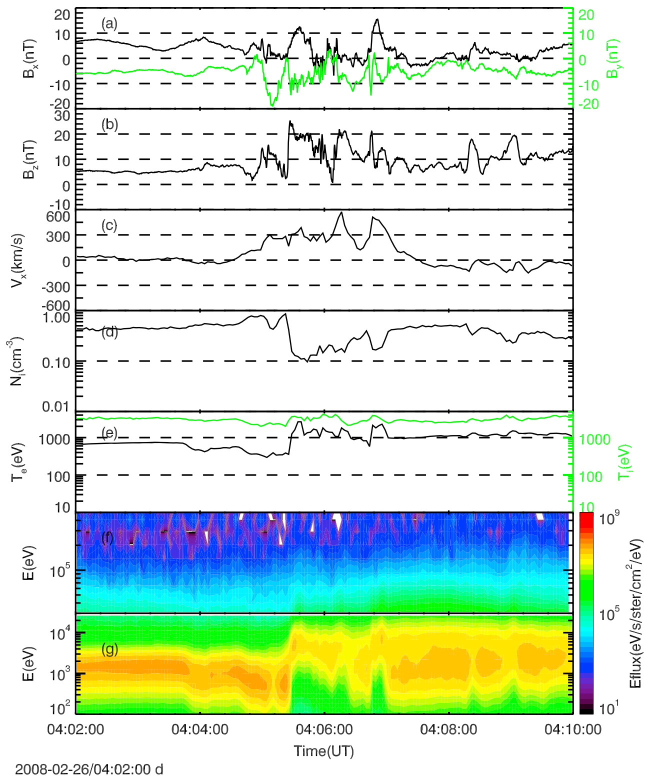

Figure 6. The magnetic field and particle data obtained by THD between 04:02 and 04:10 UT on 26 February 2008. The format is the same as in Figure 1.

3.3. Similar Events

There are also two other magnetic reconnection events in the midtail which are observed by THEMIS (list in Table 2). The multistage acceleration process can also be confirmed by these two events. This study suggests that low-energy electrons can be accelerated to a high energy with a multistage process in magnetic reconnection, which lasts from the vicinity of the X line to the BBFs.

Figures 5 and 6 show the observation results of event 1 in Table 2. Figure 5 gives the results obtained by THB at [−22.0, 4.4, −2.7] R_E, while Figure 6 is the observation results from THD at [−10.6, 4.2, −1.8] R_E. Between 03:58 and 04:10 UT on 26 February 2008 THB observed the reversal of B_z and v_x (see Figures 5b and 5c). Unfortunately, with the value of B_x we can infer that the THB seems to be in the lobe when this reversal is observed. With the reversal of B_z from negative to positive, B_y changed its value from positive to negative (see Figure 5a), which is in agreement with the prediction of the quadrupolar out-of-plane Hall magnetic field configuration. There is no available burst mode data of SST in this magnetic reconnection event. Due to the low electron temperature (about 0.3 keV near the reconnection site), we can investigate the change of the energetic electron data with the energy 8 keV~30 keV obtained by ESA instead. Figure 6 shows that THD observed a BBF leading with a sharp B_z jump which is a DF at about 04:05:22 UT. During the DF crossing, the particle density has a rapid decrease while the electron temperature has an obvious increase. As shown by Figures 6f and 6g, the energetic electron flux with energies from 15 keV to 200 keV has an increase behind the DF. The information of thermal and energetic electrons is also used to study electron acceleration process in this event. The electron temperature (black points), the energetic electron energy flux in the energy channel 20 keV (green points), and the power index (red points) in this magnetic reconnection event are given in Figure 7. The unit of T_e is eV, and energy flux is in unit of eV/(cm^2 s sr eV), and the values are the results of raising a base-10 logarithm. B_z (cyan line) is also plotted in this figure. As shown in Figure 7a we can also observe the pileup region with large B_z, rapid increase of energetic electron flux, and continuous change of power law index around 04:05:50 UT when the spacecraft was in the earthward flow near the reconnection site. In this event, energetic electron flux also increases about 100 times in this region. However, the waves are quite weak. In the pileup region, the electron temperature also has a slight increase. Figure 7b shows that just behind the DF at about 04:05:22 UT THD observed a high electron energetic electron flux. In this event, the energetic electron flux behind the DF is about an order of magnitude higher than that in the earthward flow. THE also observes similar results as THD. So in this event the electron acceleration have the similar processes. Electrons are first heated in the vicinity of X line. Then the energetic electrons in the earthward flow can further accelerate in the pileup region. Meanwhile, the electron temperature has a slight increase. At last, some adiabatic accelerations work during the earthward propagation of BBF which can lead to the further enhancement of energetic electron energy flux.

Figures 8 and 9 show the observation results of event 2 in Table 2. Figure 8 shows that the most tailward THEMIS probe THB observed a flow and magnetic field reversal, which indicated a magnetic reconnection

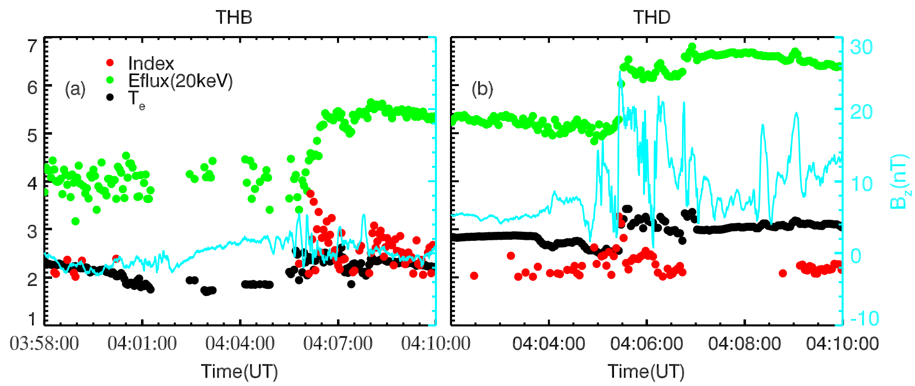

Figure 7. (left column) The magnetic field and particle data for THB between 03:58 and 04:10 UT on 26 February 2008. There are (a) electron temperature T_e (black points), energy flux of energetic electrons with the energy 20 keV (green points), and the power law index over the energy range (8 keV, 30 keV). The cyan line is B_z. (right column) The magnetic field and particle data for THD between 04:02 and 04:10 UT on 26 February 2008. The format is the same as the left column. The unit of T_e is eV, and energy flux is in unit of eV/(cm^2 s sr eV).

event. In this event, THB was located at about [−23.8, 1.4, −1.3] R_E, and THC was located at about [−18.7, 1.0, −2.2] R_E. Between 02:30 and 02:35 UT on 27 February 2009 THB observed the reversal of B_z and v_x (see Figures 8b and 8c). With the reversal of B_z from negative to positive, B_y changed its value from positive to negative (see Figure 8a), which fits the features of the quadrupole out-of-plane Hall magnetic field configuration. Unfortunately, by the value of B_x we can infer that the THB seems to be in the lobe when this reversal is observed. In this event, the electron temperature is very low. The electron temperature is only about 200 eV in the tailward flow, and in the earthward flow the electron temperature is always on the level of hundreds of eV. Due to the low electron temperature, we can investigate the change of the energetic electron data with the energy 2 keV~30 keV obtained by ESA instead. Figure 9 shows that several minutes after the observation of the reconnection site THC observed several BBFs. Because the separation of THB and THC is only 0.4 R_E in the y direction, these BBFs can be in the same flow channel with the earthward flow. As shown in Figure 9b, two DFs with sharp B_z jumping are detected by the spacecraft. One DF is at about 02:39:40 UT, and the other one is at about 02:44:51 UT. However, just after the crossing of the first DF, the large B_x and electron distributions indicate that the spacecraft travel to the south lobe immediately. So we cannot get the information of electrons behind this DF. Figure 10 shows the electron temperature (black points), the energetic electron energy flux in the energy channel 12 keV (green points), and the power index (red points) in this magnetic reconnection event. The unit of T_e is eV, and energy flux is in unit of eV/(cm^2 s sr eV), and the values are the results of raising a base-10 logarithm.

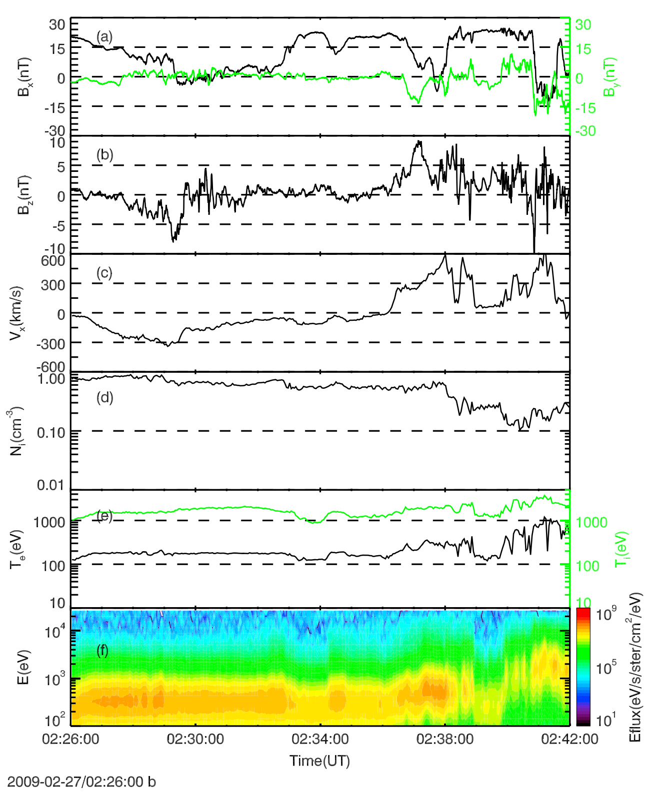

Figure 8. The magnetic field and particle data obtained by THB between 02:26 and 02:42 UT on 27 February 2009. The format is the same as in Figure 5.

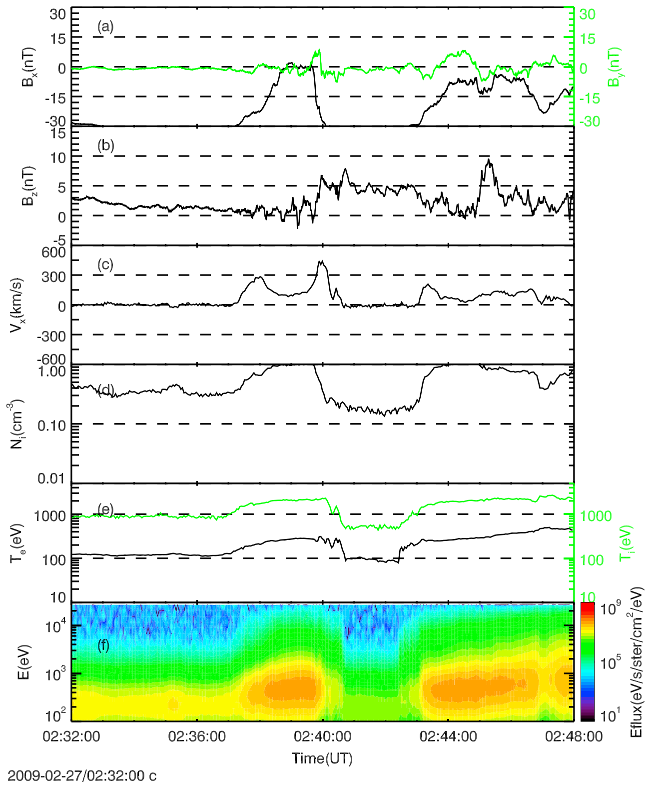

Figure 9. The magnetic field and particle data obtained by THC between 02:32 and 02:48 UT on 27 February 2009. The format is the same as in Figure 5.

The cyan lines represent B_z. In Figure 10a, the tailward flow is in the time interval 02:26–02:34 UT, and the earthward flow is in the time interval 02:36–02:42 UT. The electron temperature T_e in the tailward flow is about 0.2 keV. The value of T_e is in the range of 0.3~1.1 keV in the earthward flow, which is a bit larger than that in the tailward flow. After about 02:36:12 UT, the spacecraft starts to cross a region with large B_z in the earthward flow. Both the electron temperature and energetic electron flux in the region are larger than that in the tailward flow. Unfortunately, the spacecraft travels to the lobe soon. At about 02:41:00 UT, the spacecraft locates the plasma sheet again. Compared with the time 02:38:00 UT, the electron temperature and energetic electron flux at 02:41:00 UT are much higher than before. Additionally, the power law indices are also different at these two different times. It indicated that the nonadiabatic may also occur in this event. Figure 10b shows that just behind the DF at 02:44:51 UT THC observed a high electron energetic electron flux. In this event, energetic electron flux slowly and continuously increases behind the DF. Both the median and the maximum values of energetic electrons behind the DF are larger than that in the earthward flow. So in this event the electron acceleration have the similar processes. Electrons are first heated in the vicinity of X line. Then the energetic electrons in the earthward flow can further accelerate in the pileup region. Meanwhile, the electron temperature has a slight increase. At last, some adiabatic accelerations work during the earthward propagation of BBF which can lead to the further enhancement of energetic electron energy flux.

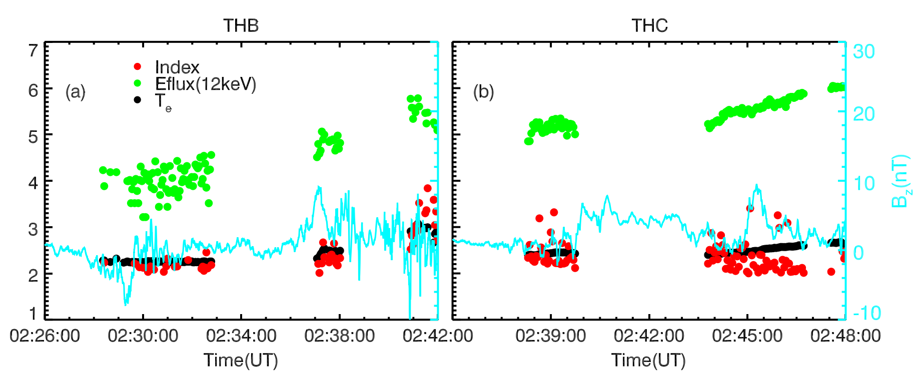

Figure 10. (left column) The magnetic field and particle data for THB between 02:25 and 02:42 UT on 27 February 2009. There are (a) electron temperature T_e (black points), energy flux of energetic electrons with the energy 12 keV (green points), and the power law index over the energy range (2 keV, 30 keV). The cyan line is B_z. (right column) The magnetic field and particle data for THD between 02:32 and 02:48 UT on 27 February 2009. The format is the same as the left column. The unit of T_e is eV, and energy flux is in unit of eV/(cm^2 s sr eV).

4. Discussion and Conclusions

With the observation of the magnetic reconnection event at 04:50:00 UT–05:10:00 UT on 26 February 2008, we find that electrons suffer a multistage process: first, when electrons are injected into the vicinity of X line from the lobe, they can be accelerated by the reconnection electric field. At this stage, the electrons are accelerated from the thermal energy to several keV, which causes the increase of the electron temperature by a factor of ~6. These electrons provide the seed particles for the further acceleration to energies up to tens of keV. After the electrons accelerated in the vicinity of X line, they can further be nonadiabatically accelerated due to the ∇B drift and/or curvature drift in the pileup region of the earthward flow. This nonadiabatic acceleration causes the slight increase of the electron temperature and a large enhancement of the energetic electron energy flux. The enhancement of the electron flux can even reach about 2 orders of magnitude. In this event, the waves are very strong in the pileup region and the wave-particle interaction can also be a possibility of electron acceleration. But in the event 1 listed in Table 2, we can find that the energetic electron flux can also increase about 2 orders of magnitude in the pileup region under weak wave condition. At last, the energetic electrons ($>$30 keV) can be continuously accelerated, whereas the power law index remains unchanged during the earthward propagation in the high-speed flow, and such an acceleration is an adiabatic process. Moreover, the distribution of the electron flux shows that this adiabatic acceleration seems to be more effective in the center of plasma sheet. At this stage, the electron flux is increased about 8.5 times. Please note that in the event the distance between the X line and the DF is only ~4 R_E and the DF will continue propagating toward the Earth. In general, a DF can propagate ~10 R_E, and the process of the adiabatic acceleration can last over a longer time span than the duration reported in this event [*Wu et al.*, 2013]. Therefore, the adiabatic acceleration associated with a DF also provides a way to produce energetic electrons with energies up to hundreds of keV. This can also be confirmed by the event 1 listed in Table 2. As shown in Figures 7a and 7b, in event 1 the energetic electron flux can increase about 1 order of magnitude from the earthward flow to the BBF.

In this paper, with the THEMIS observations of magnetotail reconnection events, we reveal the process of multistage electron acceleration in magnetic reconnection. Electrons are first heated in the vicinity of X line, and then they can be accelerated to be energetic electrons with energy from tens to hundreds of keV in the pileup region. After that, the energy flux of these energetic electrons will further increase during the earthward propagation. We propose that such a multistage process is an essential ingredient to produce energetic electrons in magnetic reconnection which happened in the midtail.

With the Geotail observations *Imada et al.* [2011] have discussed the relationship between the acceleration efficiency of energetic electrons and magnetic reconnection conditions and found their positive relation. The acceleration efficiency of energetic electrons may also depend on the different conditions of DFs, which will be our future work.

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