Electron Acceleration in a Magnetotail Reconnection Outflow Region Using Magnetospheric MultiScale Data

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Abstract We study Magnetospheric MultiScale observations in the outflow region of magnetotail reconnection. We estimate the power density converted via the three fundamental electron acceleration mechanisms: Fermi, betatron, and parallel electric fields. The dominant mechanism, both on average and the peak values, is Fermi acceleration with a peak power density of about +200 pW/m^3. The magnetic field curvature during the most intense Fermi acceleration is comparable to the electron gyroradius, consistent with efficient electron scattering. The peak power densities due to the betatron acceleration are a factor of 3 lower than that for the Fermi acceleration, the average betatron acceleration is close to zero and slightly negative. The contribution from parallel electric fields is significantly smaller than those from the Fermi and betatron acceleration. However, the observational uncertainties in the parallel electric field measurement prevent further conclusions. There is a strong variation in the power density on a characteristic ion time scale.

1. Introduction

Magnetic reconnection is a fundamental energy conversion process present in space (e.g. Paschmann et al., 2013) and laboratory environments (e.g. Yamada et al., 2010). During reconnection the changes in magnetic field topology cause efficient conversion of magnetic energy into particle energy (Birn and Priest, 2007). Most of the topological change occurs in small regions where the ions and electrons demagnetize, so-called diffusion regions. However, most of the energy conversion occurs on scales much larger than diffusion regions. On large scale magnetic reconnection leads to the formation of plasma jets. Inside the plasma jets, so-called outflow regions, efficient but not fully understood particle energization processes take place. Here we focus on electron energization, which is particularly important in astrophysical context, where electromagnetic radiation generated by accelerated electrons enables remote observations of reconnection regions, such as those in solar flares (Petrosian, 2016). The new observational data from Magnetospheric MultiScale (MMS) mission (Burch et al., 2016) allows to advance the understanding of the electron energization mechanisms in reconnection.

Different electron acceleration mechanisms related to reconnection have been explored and compared in theory, simulations, and observations (Hoshino et al., 2001; Egedal et al., 2010; Hoshino, 2012; Fu et al., 2013; Graham et al., 2016; Eriksson et al., 2018). In the guiding center approximation there are three fundamental acceleration mechanisms: Fermi acceleration due to the particle motion in curved magnetic field, betatron acceleration associated with the conservation of the magnetic moment, and acceleration by localized parallel electric fields. The change in the total kinetic energy density of electrons $U$ due to these mechanisms can be written as

$$\frac{dU}{dt} = \frac{p_\perp}{|B|} \left( \frac{\partial |B|}{\partial t} + \mathbf{u}_\parallel \cdot \nabla |B| \right) + \left( p_\parallel + m_e n_e v_{\|}^2 \right) \mathbf{u}_\parallel \cdot \mathbf{c} - n_e e v_{\parallel} E_\parallel \equiv W_{\text{Betatron}} + W_{\text{Fermi}} + W_{\text{E} \parallel},$$

where $B$ and $E$ are the magnetic and electric field, $\mathbf{c} = \mathbf{b} \cdot \nabla \mathbf{b}$ is the curvature of $B$, $\mathbf{b} = B/|B|$, $\mathbf{u}_\parallel = (\mathbf{E} \times \mathbf{B})/B^2$, $v_{\parallel}$ is the electron bulk velocity parallel to the magnetic field, $n_e$ is the electron density,
$p^\parallel$ and $p^\perp$ are the electron pressure parallel and perpendicular to $\mathbf{B}$, and $E^\parallel$ is the electric field parallel to $\mathbf{B}$, respectively (Dahlin et al., 2014; Northrop, 1963). The three terms correspond to the power density of electron acceleration due to the betatron acceleration, $W_{\text{Betatron}}$, Fermi acceleration, $W_{\text{Fermi}}$, and acceleration by $E^\parallel$, $W^\parallel$. These three terms have previously been estimated in numerical simulations of reconnection (Dahlin et al., 2014; Zhou et al., 2018). Note that equation (1) describes only the first-order terms in the guiding center approximation and neglects, for example, nonadiabatic acceleration mechanisms and scattering (Wang et al., 2016; Zhou et al., 2018). In Dahlin et al. (2014) two different runs of 2-D particle-in-cell simulation are analyzed; one with a guide field of 20% and the second with a guide field comparable to the reconnecting field component. In the first case the Fermi acceleration is found to be the dominant electron acceleration mechanism, whereas in the second case the acceleration by $E^\parallel$ is found to be comparable to the Fermi acceleration. In both cases, the betatron acceleration is found to be negligible. Furthermore, both cases show that the largest contribution from Fermi acceleration occurs in the reconnection outflow regions and at the ends of magnetic islands, while the largest contributions of $E^\parallel$ are localized close to the X-line. In Zhou et al. (2018) a large-scale kinetic 3-D simulation based on an observed THEMIS magnetotail reconnection event is analyzed where the guide field is 10%. They find that acceleration by $E^\parallel$ is the dominant acceleration mechanisms and contrary to Dahlin et al. (2014) betatron acceleration is not negligible, instead $W_{\text{Betatron}}$ is much larger than $W_{\text{Fermi}}$. They also find that an ion-scale flux rope plays an essential role in accelerating the electrons. To determine the relative importance of the different electron acceleration mechanisms it is important to carry out similar detailed studies on observational data.

The power densities $W_{\text{Fermi}}$, $W_{\text{Betatron}}$, and $W^\parallel$ have to our knowledge not been estimated experimentally before. However, the total electromagnetic energy conversion to ions and electrons, $\mathbf{E} \cdot \mathbf{J}$, has been estimated in earlier studies. For example, Hamrin et al. (2015) uses Cluster data (Escoubet et al., 2001) to study $\mathbf{E} \cdot \mathbf{J}$ as a way of identifying the reconnection regions in the Earth’s magnetotail. They find that regions with $\mathbf{E} \cdot \mathbf{J} > 20 \text{ pW/m}^3$ are likely associated with reconnection. Their largest observed values of $\mathbf{E} \cdot \mathbf{J}$ are of the order 500–700 pW/m$^3$. Values of several hundreds pW/m$^3$ have been found also using MMS observations close to the reconnection sites (Torbert et al., 2018). To observationally estimate the power density due to the three electron acceleration mechanisms requires high-resolution electron measurements of the MMS mission.

2. Observations

We study electron acceleration in an outflow region of magnetotail reconnection using MMS data. During the studied time interval, 6 July 2018 15:28:00-15:33:30 UTC, MMS is in the plasma sheet close to the current sheet (CS) center. MMS observes several CS crossings and tailward jets throughout most of the interval. We particularly focus on one event, the CS crossing around 15:29:20.

2.1. Overview of the Interval

Figure 1 shows an overview of the interval and the location of MMS, the event studied in details is marked in blue. MMS is located in the middle of the magnetotail at about 24 Earth radii ($R_E$) from Earth, see Figures 1a and 1b. The largest interspacecraft separation is 18 km, which is comparable to the electron inertial length of about 14 km. Due to close separation, the different spacecraft observe almost identical measurements of fields and particles. Four spacecraft averages are used in Figure 1. All electron data are averaged to the ion measurement cadence of 150 ms thus reducing the statistical errors due to low number of counts. For easier comparison, the magnetic field is also resampled to the same cadence. All vectors are given in Geocentric Solar Magnetospheric coordinates. Observations of fast tailward jets seen in both ions and electrons, in combination with heating of both ions and electrons, and MMS being often close to the CS center ($B_y = 0$), indicates that during most of the interval MMS is in an outflow region of a tailward reconnection jet.

Figure 1c shows $\mathbf{B}$ measured by the fluxgate magnetometer (Russell et al., 2016). We observe large variations in $\mathbf{B}$, in particular, several reversals of $B_y$ suggesting crossings of the CS center. In a simple 2-D reconnection picture with one X-line, the outflow region tailward of the X-line would have negative $B_y$ values. Figure 1c shows that $B_y$ is on average negative; however, there are large fluctuations and during some periods $B_y$ is significantly positive. Similarly, we would expect to observe the reconnection Hall fields in $B_x$, in a tailward jet we expect $B_x < 0$ for $B_y > 0$ and $B_x > 0$ for $B_y < 0$. Such a relation is present only on average and in many regions the relation is not valid. Earlier observations and simulations suggest that such discrepancies...
Figure 1. Overview of the outflow region in GSM coordinates. (a, b) MMS location, the blue line illustrates the MMS trajectory during 6 July 2017. Four spacecraft average values of (c) $B$, (d) $n_e$, (e) $V_i$, (f) $V_e$, (g) power density due to Fermi acceleration, betatron acceleration, and acceleration by $E_E^{||}$, (h) electron omnidirectional differential energy flux, the black line gives electron temperature, and (i) ion omnidirectional differential energy flux. The black dashed lines in panels (h) and (i) indicate the energy level below which data were not used to calculate moments.

can be due to flapping of the magnetotail (Laitinen et al., 2007), the presence of magnetic islands (Zong et al., 2004), and/or more complicated 3-D structures (Daughton et al., 2011). The complicated nature of the interval is supported by the difficulty of finding a local coordinate systems for each CS crossing.

Figure 1d shows $n_e$ obtained from the Fast Plasma Investigation (Pollock et al., 2016). To remove the impact of background contaminations at low energies, the particle moments have been recalculated ignoring all data below about $\sim 100$ eV. During the interval $n_e$ is on average 0.16 cm$^{-3}$; however, $n_e$ shows variations ranging from $\sim 0.05$ cm$^{-3}$, when MMS is in lobe-like plasma, to $\sim 0.4$ cm$^{-3}$ for one of the CS crossings.

Figures 1e and 1f show the ion $V_i$ and electron $V_e$ velocities. Over a large part of the interval the main ion flow is tailward, of the order of 1,000 km/s, consistent with MMS being in an outflow region of reconnection. The flow velocity is reduced around 15:29:30 and 15:32:45 corresponding to regions of more lobe-like plasma. At the end of the interval, when MMS is close to the CS center, the flow velocity goes to zero. It could be that the reconnection process is switched off at the end of the interval or that MMS is approaching close to the X-line. During the interval $V_{iy}$ is on average positive, but small in comparison to the magnitude of $V_{ix}$, while $V_{iz}$ varies around zero. The electron velocity is on average similar to the ion velocity, the main flow being in the tailward direction. However, $V_e$ shows much larger fluctuations than $V_i$, $V_{ex}$ varies between about $-3,000$ and $+3,000$ km/s. Part of this variation can probably be attributed to the reconnection Hall currents, for example, the large earthward flows around 15:29:40 when MMS enters the more lobe-like plasma.

Figure 1g shows the estimated power density of the three electron acceleration mechanisms: $W_{\text{Fermi}}$, $W_{\text{Betatron}}$, and $W_{E^{||}}$. The values are estimated using equation (1), where curvature and magnetic field gradients are obtained from four spacecraft measurements (Paschmann and Daly, 1998) and the electric field in $W_{E^{||}}$ is measured by the electric field double probes (Ergun et al., 2016; Lindqvist et al., 2016). During the interval all terms show both negative and positive values. On average, $W_{\text{Fermi}}$ is positive throughout the interval, while $W_{\text{Betatron}}$ is close to zero and slightly negative. $W_{E^{||}}$ has the lowest value of all three terms and
Figure 2. Detailed observations of the selected event. Four spacecraft average (a) $B$; (b) $j$; (c) $V_i$; (d) $V_e$; (e) $T_\parallel$ and $T_\perp$; (f) $W_{\text{Fermi}}$; (g) $W_{\text{Betatron}}$; (h) $W_{\text{E}}$; the yellow region indicates the observational uncertainties from $E_\parallel$; (i) $\kappa$; (j) $\gamma$; (k–m) pitch angle electron distribution (k) 1–3 keV, (l) 3–20 keV, (m) for 5.47 keV. The magenta dashed lines indicate the crossings of CS center, regions A and B are explained in the text.

its magnitude is lower than the uncertainties in $E_\parallel$ measurement (not shown). During the interval, almost all of the peak values in power density are due to the Fermi acceleration. The power density due to the three acceleration mechanisms is close to zero when MMS is in the lobe-like plasma.

Figures 1h and 1i show the electron and ion omnidirectional differential energy flux. The electron temperature (black line) is overlaid on top of the electron spectrogram. Throughout the interval is present a hot 1–3 keV plasma sheet population of electrons. At about 15:29:30, 15:32:45, and 15:33:25 we observe a decrease in electron flux and density consistent with MMS crossing into a more lobe-like plasma. In the middle of the interval electrons are hotter and the jet velocities are higher. During this period the electron spectrogram shows much higher temporal variations than in the beginning and end of the interval, consistent with the observations of larger power density due to the Fermi and betatron acceleration. Thus, the decrease of ion velocity in the middle of CS at the end of the interval is more likely due to the reconnection being turned off than MMS entering region closer to the X-line. The ion measurements show properties similar to the electrons: a decrease in ion flux when MMS enters lobe-like regions and a hotter ion population including stronger temporal variations in the middle of the interval. Within this period of hotter plasma sheet population we have selected a shorter event (marked blue) with one of the highest power density values for a closer study of the electron acceleration mechanisms.
2.2. Event Description

We analyze in detail the electron acceleration for the selected event (marked blue in Figure 1), see Figure 2. During the event $B_z = 0$ (Figure 2a magenta dashed lines) is crossed 3 times, suggesting that MMS crosses the CS center 3 times. To help the later discussion we have marked the region between the first and second CS crossing as “A” and the second and third CS crossings as “B.” $B_z$ is predominantly negative during the entire event, suggesting that MMS is crossing the outflow region tailward of an X-line. $B_z$ does not show the typical signatures expected for the Hall field, but as mentioned before this could be due to flapping or more complicated structures.

Figure 2b shows $j$ derived from the curlometer method, the values are very close to the current values obtained from particle moments (not shown). During this event $j_y$ is mostly positive as expected for a cross-tail current, while $j_x$ and $j_z$ show intervals of both positive and negative values and we cannot identify a simple picture that would fit their sign and magnitude.

Figures 2c and 2d show $V_i$ and $V_e$, respectively. For both ions and electrons the dominant component is large negative $V_x$ consistent with MMS crossing the tailward outflow region. The electron velocity shows more variations than the ion velocity, $V_{en}$ is varying between $-2,000$ and $-210$ km/s. Figure 2e shows the electron temperature parallel $T_{\parallel}$ (black) and perpendicular $T_{\perp}$ (red) to $B$. The electron temperature varies between about 2,100 and 2,900 eV. The electron temperature is very close to isotropic; however, during the periods of hottest plasma $T_{\perp}$ can be about 100–200 eV larger than $T_{\parallel}$.

Figures 2f–2h show the power densities $W_{\text{Fermi}}$, $W_{\text{Betatron}}$, and $W_{Eij}$. In Figure 2f we observe three large peaks in $W_{\text{Fermi}}$ during each consecutive crossing of the CS center. The peak values decrease from 200 to 130 to 30 pW/m$^3$ between the first and third CS crossing. Near each peak of $W_{\text{Fermi}}$ we also observe a positive peak in $W_{\text{Betatron}}$ (Figure 2g) that is surrounded on both sides by regions of negative $W_{\text{Betatron}}$. The positive peak values of $W_{\text{Betatron}}$ in the CS center are by a factor of 3 smaller than the peak values of $W_{\text{Fermi}}$. Similar to $W_{\text{Fermi}}$, there is a big decrease in the peak values of $W_{\text{Betatron}}$ between the first and third CS crossing. $W_{Eij}$ (black line in Figure 2h) shows on average peak values of about a factor of 25 less than $W_{\text{Fermi}}$. However, the observational uncertainties in $W_{Eij}$ (marked yellow), caused by the uncertainties in the $E_{ij}$ measurement, are larger than the $W_{Eij}$ magnitude. Therefore, we cannot draw any further conclusions regarding $W_{Eij}$.

Figures 2i and 2j show the magnetic field curvature $\kappa$ and the square root of the ratio between the electron gyroradius and radius of the magnetic field curvature, $\gamma$. The largest $|\kappa|$ values are in the center of each CS crossing and the largest component of $\kappa$ is in negative $x$ direction consistent with MMS being in the tailward outflow region. The peak values of the curvature and $\gamma$ decrease from the first to the last crossing of the CS center, Figures 2i and 2j. The values of $\gamma$ are small throughout most of the event but the largest peak value of $\gamma = 0.85$ is observed during the first crossing of the CS center. Büchner and Zelenyi (1989) show that $\gamma$ can be used to determine the efficiency of electrons scattering. The values of $\gamma$ close to 1 indicates an efficient scattering and possibly nonadiabatic motion of electrons. The observed values of $\gamma$ suggest that during the first crossing of the CS center there should be an efficient scattering of electrons, while inside the second and particularly the third crossing the scattering should be less efficient.

In Figures 2k–2m we show electron pitch angle distributions at different energies. Figure 2k shows the electron pitch angle distribution of thermal electrons in the range 1–3 keV. During most of the event the distribution is close to isotropic, but during a few shorter time periods narrow beams in parallel and antiparallel directions are observed. The most intensive parallel (antiparallel) beams are correlated with $B_z > 0$ ($B_z < 0$).

Figure 2l shows the electron pitch angle distribution in the range 3–20 keV. First, there is more flux in the antiparallel direction before the first CS crossing and in the region B. Second, there is an increase in electron fluxes close to the parallel direction inside region A. Third, there are increased fluxes in the perpendicular direction inside the region A and at the last CS crossing. To clearly illustrate the acceleration processes we show electron fluxes in Figure 2m for only one energy channel 5.47 keV. In general, it shows the same properties as Figure 2l. However, it shows the increased parallel electron fluxes in region A more clearly.

3. Discussion

Most of the observations in Figure 2 are consistent with the electron acceleration ongoing according to a simplified sketch of a 2-D reconnection outflow region in Figure 3, where the green line indicates a spacecraft trajectory consistent with observations. In this simplified picture, we expect to observe the largest values
mechanisms, but instead looked at our observational studies have not been able to separate the power density due to the different acceleration mechanisms. We compare our results with a few available studies from numerical simulations and observations. Previous predictions of the relative importance of different acceleration mechanisms can be done with numerical simulations; however, numerical simulations themselves give different predictions. Our event (and also the full interval in Figure 1) shows that the average power density due to Fermi acceleration is dominating all other processes and that the average of betatron acceleration is close to zero being slightly negative. These observations are consistent with numerical simulation results by Hamrin et al. (2015). The sum of our values are also well above 20 pW/m$^3$, suggested by Hamrin et al. (2015) as an indicator of a reconnection event. More detailed comparison of the relative importance of different acceleration mechanisms in the flux rope changes on a time scale of seconds. Thus, our observations support Zhou et al. (2018) suggesting the formation of a flux rope and how the relative importance of different acceleration mechanisms in the spatial/temporal evolution of the CS that cannot be described by this sketch. This is consistent with the results found in the 3-D numerical simulation by Zhou et al. (2018) showing the formation of a flux rope and how the relative importance of different acceleration mechanisms in the flux rope changes on a time scale of seconds. Thus, our observations support Zhou et al. (2018) suggestion that time-dependent structures need to be taken into account to understand the electron acceleration in magnetic reconnection.

During the event we observe that between the first and last CS crossing the CS properties significantly change. This occurs on a time scale of about 5 s that is comparable to the ion gyroperiod. On this time scale, the peak power densities of the Fermi and betatron acceleration decrease with each crossing, the curvature radius increases, the scattering efficiency decreases, and the pitch angle properties of the electron distribution change. This suggests that even though the sketch in Figure 3 matches well many of the observations, there is a significant complexity in the spatial/temporal evolution of the CS that cannot be described by this sketch. This is consistent with the results found in the 3-D numerical simulation by Zhou et al. (2018) showing the formation of a flux rope and how the relative importance of different acceleration mechanisms in the flux rope changes on a time scale of seconds. Thus, our observations support Zhou et al. (2018) suggestion that time-dependent structures need to be taken into account to understand the electron acceleration in magnetic reconnection.

We compare our results with a few available studies from numerical simulations and observations. Previous observational studies have not been able to separate the power density due to the different acceleration mechanisms, but instead looked at $E \cdot j$, which is the total power density of energy conversion to both ions and electrons. The sum of our values of $W_{\text{Betatron}}$, $W_{\text{Fermi}}$, and $E \cdot j$ for the peak values is of the order 300 pW/m$^3$. This is of the same order as the peak values of $E \cdot j$ observed in the magnetotail by Cluster (Hamrin et al., 2015). The sum of our values are also well above 20 pW/m$^3$, suggested by Hamrin et al. (2015) as an indication of a reconnection event. More detailed comparison of the relative importance of different acceleration mechanisms can be done with numerical simulations; however, numerical simulations themselves give different predictions. Our event (and also the full interval in Figure 1) shows that the average power density due to Fermi acceleration is dominating all other processes and that the average of betatron acceleration is close to zero being slightly negative. These observations are consistent with numerical simulation results by Hamrin et al. (2015).
Dahlin et al. (2014) but inconsistent with Zhou et al. (2018). These discrepancies could possibly be due to the temporal variation of the different processes and/or due to the presence of flux tubes in the simulation by Zhou et al. (2018). Similarly, for this event we could not assess detailed properties of $W_{E_{\parallel}}$ due to the observational uncertainties in the $E_{\parallel}$ measurements. However, we conclude that the $E_{\parallel}$ acceleration is much less important than the Fermi acceleration. This is consistent with what was reported for the low guide field case in Dahlin et al. (2014), but inconsistent with Zhou et al. (2018). Wang et al. (2016) analyze electron acceleration in the outflow region using test particles and conclude that $E_{\parallel}$ can be important but the contribution from each of the acceleration processes on a full distribution function locally are not estimated. Thus, more observations and numerical simulation studies are required to determine the importance of $E_{\parallel}$ acceleration.

4. Conclusions

We show the first experimental estimates of the electron acceleration power densities in a reconnection outflow region due to the three mechanisms: Fermi acceleration, betatron acceleration, and acceleration due to $E_{\parallel}$. We have selected one event for detailed study. During the event MMS is in an outflow region, tailward of a reconnection X-line, and observes one of the highest electron acceleration power densities. On average, the Fermi acceleration dominates while $W_{\text{Betatron}}$ is near zero and slightly negative, thus there is no essential average effect due to the betatron acceleration. When comparing peak power density values, $W_{\text{Fermi}}$ has the largest peak of 200 pW/m$^3$, while $W_{\text{Betatron}}$ peak is 70 pW/m$^3$. $W_{\text{Fermi}}$ shows predominantly positive values during the whole event, while $W_{\text{Betatron}}$ varies between positive and negative values. $W_{E_{\parallel}}$ has the lowest values of all acceleration mechanisms, however, the observational uncertainties in $W_{E_{\parallel}}$ caused by the uncertainties in the $E_{\parallel}$ measurement, is larger than the $W_{E_{\parallel}}$ magnitude. Thus, we cannot draw any further conclusions of $W_{E_{\parallel}}$. Our results are partially consistent with the results from existing numerical simulations; however, there is no consistent picture on the relative importance of different electron acceleration mechanisms in the current simulation studies.

We show that during some of the crossings of the outflow region the local curvature radius can become comparable to the gyroradius of electrons. In these regions electron distribution functions become more isotropic. This is consistent with efficient scattering of electrons proposed in Büchner and Zelenyi (1989) and could suggest that electrons can be locally nonadiabatic in the current sheet center.

We show that the local electron acceleration is consistent with the predictions from a simplified 2-D reconnection picture. The peak values of the power density due to the Fermi and betatron acceleration are observed close to the current sheet center. However, the peak values show large variation between the first and last current sheet crossing. This suggests that even though the simplified 2-D picture matches many of the observations well, there is a significant complexity in the spatial/temporal evolution of the current sheet that cannot be described by a simplified model. Despite variations, the Fermi acceleration is the dominant electron acceleration mechanism during the whole event.

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Acknowledgments

We thank the entire MMS team and instrument PIs for data access and support. This work was supported by the Swedish Research Council, Grant 2013-4309. MMS data are available at this site (https://lasp.colorado.edu/mms/sdc/public).
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