Storm and substorm effects on magnetotail current sheet motion

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[1] Passes through the mid-region of the magnetotail by the Cluster spacecraft from 2001 to 2007 have been examined to study the dynamics of the cross-tail current sheet. Cluster is ideally placed to study this region due to the orientation of the orbit in the magnetotail, such that the current sheet is sampled at distances downtail from about 8–19 Rₑ. Multiple fluctuations of the X component of the magnetic field (Bₓ) from positive to negative and vice versa, measured by Cluster as it crosses the nominal location of the current sheet, indicate that the current sheet is in motion. In this study we use the number of crossings of the current sheet by the Cluster 3 spacecraft as a measure of the dynamics of the magnetotail. The effects of substorm and magnetic storm activity on the dynamics during these orbits have been investigated using the AE and SYM-H indices. Our results indicate that the current sheet is more often in motion during orbits when there is greater than average substorm activity and a quiet ring current. Results suggest that internal processes within the tail that initiate substorms may also initiate the flapping motion of the current sheet. In addition the more dipolar field that results from an enhanced ring current during magnetic storms may inhibit tail dynamics during substorm events.


1. Introduction

[2] The Earth’s magnetotail current sheet, located in the center of the plasma sheet, is a boundary layer separating the opposing magnetic fields of the lobes. The current is directed dawn-to-dusk and understanding the properties of the current sheet is important, due to its significance in substorm and storm processes.

[3] There is evidence that the current sheet is a dynamic region. Its motion is often described as a flapping movement in a North-south direction [Speiser and Ness, 1967], either from the center of the tail propagating out toward the flanks [e.g., Lui et al., 1978; Nakagawa and Nishida, 1989] or in a direction along the tail [e.g., Speiser, 1973]. The cause of this current sheet motion is unknown, although two explanations have been investigated in the literature. The propagation of the motion from the center of the tail toward the flanks may indicate that it is initiated in the center of the tail within the current sheet and caused by some internal mechanism, for example substorm activity [e.g., Sergeev et al., 2004]. External influences have also been studied, investigating how changes in the solar wind dynamic pressure may affect the current sheet motion [e.g., Forsyth et al., 2009].

[4] Runov et al. [2005] used the Cluster spacecraft to investigate three cases of current sheet motion employing data from 2001, during which the current sheet was in motion. They described the periods as ‘active’ and showed that the current sheet was strongly tilted in the Y-Z plane as the current sheet moved over the Cluster spacecraft. Zhang et al. [2005] investigated a series of spacecraft crossings of the current sheet on 5 August 2004. They found that the crossings were due to a kink-like wave which propagated within the current sheet from the center of the tail toward the flanks. They viewed this wave at two positions in the tail, at XGSE = −11 Earth Radii (Rₑ) and −16 Rₑ, using Double Star (TC-1 Satellite) and Cluster observations respectively. Further evidence of a strongly tilted sheet in the Y-Z plane and propagation in the dawn-dusk direction has been found in other case studies and statistical studies [e.g., Zhang et al., 2002; Sergeev et al., 2003; Runov et al., 2003].

[5] The association between substorm activity and current sheet dynamics was studied by Bauer et al. [1995] who found that current sheet motion occurred close to substorm onset. This was confirmed by Sergeev et al. [1998]. Later, following the launch of the multispacecraft Cluster mission, Runov et al. [2006] studied current sheet crossings between July and October 2001. They investigated whether there was any dependence on the structure and thickness of the current sheet with the AE index. No correlation was found, although the data set was considered too small for a complete analysis. In contrast, Sergeev et al. [2006] did find a correlation between substorm expansion phases based on the AE index and flapping motions of the current sheet. However, there were also a significant number of flapping motions when the AE index was low. They also found some evidence that the flapping of the current sheet is related to the occurrence of Bursty Bulk Flows (BBFs). In addition, Milan et al. [2006] discussed current sheet motions associated with substorm intensification, during an interval in 2004. Runov et al.
[2009] observed flapping events during a five hour period in December 2007, using the THEMIS spacecraft, during substorm growth phases, identified using THEMIS ground-based magnetometers. Forsyth et al. [2009] observed current sheet motion which occurred after two substorms following a solar wind pressure pulse. No conclusions could be made regarding the relationship between the motion and substorms due to the presence of the solar wind pulse which caused an oscillation of the plasma sheet.

How the current sheet responds to an enhanced ring current, such as exists during magnetic storms, remains an unanswered question. Milan et al. [2008] studied the expansion and contraction of the polar cap in response to variations in the solar wind conditions. They found that the polar cap size (giving an indication of the amount of open flux in the magnetosphere) increases during magnetic storms. Consequently, they suggested that the enhancement of the ring current that occurs during storms may result in an increase in the amount of open flux needed for the commencement of tail reconnection and thus stabilize the tail to substorm initiation.

In order to test this hypothesis and investigate the effect of substorms on the current sheet, our study investigates the motion of the current sheet in a global context. We consider orbits of the Cluster 3 spacecraft through the magnetotail and study overall effects of substorms on the dynamics of the current sheet, rather than individual crossings. The Cluster spacecraft enable an investigation of these effects due to their orbit passing through the mid region of the magnetotail, which is of significance in substorm processes. They also provide data of successive passes through the current sheet, enabling a study of its vertical motion. We focus on the number of current sheet crossings by the Cluster 3 spacecraft for each orbit through the magnetotail as a measure of the dynamic nature of the tail during each orbit. We use the auroral electrojet index as a measure of substorm occurrence, for the period of time that the crossings occur. In addition we employ SYM-H data to investigate whether magnetic storms have a stabilizing effect on the motion of the current sheet.

This study employs data from ESA’s Cluster spacecraft [Escoubet et al., 2001], which have an apogee of approximately 19 R_E. Launched in 2000, the Cluster mission comprises 4 spacecraft, each with 11 instruments, investigating magnetic and electric fields, particle populations and waves. The instruments used in this study are the Fluxgate Magnetometer (FGM) [Balogh et al., 2001; Gloag et al., 2010] and the CODIF (CIS) instruments [Rème et al., 2001; Dandouras et al., 2010], both from the Cluster 3 spacecraft only. The data used are at spin resolution, obtained from the Cluster Active Archive (CAA) [Perry et al., 2006; Laakso et al., 2010]. SYM-H data [Iyemori, 1990] from the WDC for Geomagnetism, Kyoto, is derived from low latitude ground-based magnetometers, providing a 1-minute resolution measure of the longitudinally symmetric disturbance in the horizontal component of the geomagnetic field at the equator. These data provide an indication of the strength of the ring current and thus of the presence of magnetic storms. The 1-minute resolution Auroral Electrojet (AE) index [Davis and Sugiura, 1966] has also been used in this study to provide an indication of substorm occurrence. The AE index is a measure of the overall horizontal current in the auroral region and can be used as an indication of the presence of substorms.

3. Observations

3.1. Selection of Data Set

In order to study the dynamics of the current sheet, we have created a database of each orbit of the Cluster 3 spacecraft through the mid region of the magnetotail, setting an inner limit at $X = -8 \text{ R}_E$ and a maximum distance downtail equivalent to the distance at apogee at approximately $X = -19 \text{ R}_E$. We have identified the number of current sheet crossings within each orbital pass through the region, thereby viewing the orbits as a whole. This allowed us to investigate current sheet activity within one orbital pass, during magnetic storms, substorms and quiet conditions. The data comprised orbits from July/August to October/November of each year, from 2001 to 2007.

We have used the X (GSM) component of the magnetic field ($B_X$) measured by Cluster 3 to identify the crossings of the current sheet and thereby study its motion. $B_X$ is positive in the north lobe of the magnetotail, passing though $B_X = 0$ in the current sheet, and is negative in the south lobe. Current sheet motion is identified when $B_X$ is seen to fluctuate about $B_X = 0$. We have defined a crossing of the current sheet as a change in $B_X$ from $+5 \text{ nT}$ to $-5 \text{ nT}$ or vice versa and counted the crossings for each orbit. This criterion resulted in a data set of part-orbits through the magnetotail, with one or more crossings of the current sheet in each orbit. In addition, we have also considered smaller and larger changes in $B_X$, to assess the impact of different thresholds on the results. As well as using a $\pm 5 \text{ nT}$ threshold in $B_X$, we also use $\pm 3 \text{ nT}$ and $\pm 7 \text{ nT}$ thresholds in $B_X$ in this paper. The $B_X$ threshold criteria used in this study are different from those employed in other studies [e.g., Runov et al., 2006]. Other studies investigated the flapping motion of the current sheet by considering larger changes in $B_X$ and limiting the time duration of each crossing. We have employed simple criteria to consider more general motion of the current sheet. Examples of orbits with current sheet crossings are shown in Figure 1. Figure 1a shows the $B_X$ component from an orbit with only one $\pm 5 \text{ nT}$ crossing as defined by our criterion, indicating a stable current sheet. Figure 1b shows the $B_X$ component from an orbit with 19 crossings at the $\pm 5 \text{ nT}$ threshold, indicating a more dynamic current sheet. By comparison to the number of 5 nT crossings for the orbits shown in Figure 1, Figure 1a contains only one (nine) crossing at the $\pm 7 \text{ nT}$ ($\pm 3 \text{ nT}$) threshold and Figure 1b contains 13 (23) at the $\pm 7 \text{ nT}$ ($\pm 3 \text{ nT}$) threshold.

In order to minimize undetected crossings due to data gaps, orbits with data gaps of more than 480 s in the region where the crossings occurred, were removed from the data set. In addition, Cluster enters the magnetosheath during some of its orbits, where the spacecraft are toward the flanks of the tail. The magnetosheath is where the magnetic field is highly variable in nature and plasma densities can reach $20 \text{ cm}^{-3}$ [Sibeck and Gosling, 1996]. It is therefore highly probable that $B_X$ variations on orbits which cut through the flanks of the tail could be due on occasion to the
spacecraft passing into the magnetosheath rather than current sheet motion. Thus, in order to ensure that crossings into the magnetosheath have been removed such that magnetic field fluctuations measured were due to current sheet motion alone, two further criteria were employed. Orbits with a maximum H+ number density of more than 1.5 cm$^{-3}$ were not included. In addition, orbits with crossings in the flanks of the tail (|Y (GSM)| > 10 R$_E$) were removed. The resulting database comprised 128 orbits from 2001 to 2007, as H+ density data are currently unavailable in the CAA after 2007. The final data set included orbits from August to November due to the restrictions set in Y(GSM).

Figure 2 shows the distribution of the positions of the crossings for all data, with each line representing a 5 nT crossing. The limits in the X and Y directions (GSM) are due to the orbit of the spacecraft and the limits in Y defined above. The positions of the crossings in the Z (GSM) direction range from about −4 to +5 R$_E$. Figure 2 (middle) shows a tilt in the position of the crossings in YZ plane using data from 2001 to 2007. This tilt was also observed by Petrukovich et al. [2005], who used data from Cluster’s

![Figure 1](image1.png)  
**Figure 1.** Examples of crossings of the current sheet by the Cluster 3 spacecraft, indicated by changes in B$_X$ between +5 and −5 nT and vice versa. (a) A stable current sheet (with 1 crossing). (b) A more dynamic current sheet (with 19 crossings).

![Figure 2](image2.png)  
**Figure 2.** Position of crossings, shown by each black line. Positions are shown in the XZ, YZ and XY GSM planes. The lines shown for each crossing cover the positions of the start and end of each crossing as defined by a change in B$_X$ between at least +5 and −5 nT.
2001–2003 tail seasons. They noted that the macroscale position of the current sheet in the YZ plane was due to changes in the dipole tilt orientation over time. Similar YZ tilts were observed by Zhang et al. [2006] who used 2001 and 2002 Cluster tail season data and by Rong et al. [2010] who used 2001–2005 Cluster data.

Figure 3a presents the distribution of the number of 5 nT crossings per orbit for the whole data set. Almost half of the orbits contain only 1 crossing, implying that the current sheet is in a stable condition for half the time, based on this criterion. The mean number of crossings is 5 and 63% of the orbits have less than the mean number of crossings. In the 128 orbits within the database, there were 648 crossings using the ±5 nT threshold. For comparison, Figures 3b and 3c show the distribution of number of crossings per orbit for the 3 nT and 7 nT crossings respectively. In comparison to the ±5 nT crossings, within the 128 orbits in the database there were 445 (1022) crossings using the ±7 nT (±3 nT) threshold. The mean number of crossings is 3.5 for the 7 nT threshold and 8 for the 3 nT threshold.

Figure 4 shows the distribution of mean number of crossings per orbit per year in red using the left-hand Y-axis. The mean number of crossings peaks in 2002 and is then followed by a decline up to 2007. The standard error of the mean is shown by vertical lines through the center of each bar. Figure 5 shows selected orbits from August 2002 and 2007. The point of apogee for each of the orbits changes over the years under study, meaning that the passes through the current sheet are not at the same position in the tail nor do the Cluster spacecraft pass through the current sheet at the same angle. Those passes at an angle away from the current sheet normal will spend longer in the vicinity of the current sheet than those following a path along the normal. In addition, the slices through the current sheet are not in the same section of the orbital path. As a result of these issues,
when the spacecraft spends more time in the current sheet, it is more likely that motion will be observed.

[15] In order to remove any orbital effect the number of crossings per orbit was normalized to the amount of time spent between $+3 R_E$ and $-4 R_E$ in the Z GSM direction. For each orbit, the number of crossings was divided by the time spent in the aforementioned region, resulting in a normalized number of crossings per hour per orbit. A more detailed explanation of this method is discussed in section 3.3. Figure 4 shows the distribution of the mean number of normalized crossings per year in blue using the right-hand Y-axis. The mean number of normalized crossings per hour per orbit is shown by vertical lines in the center of each bar.

The AE index is a measure of electrojet activity. We have used the standard deviation of the AE index during the time duration of the crossings as an indication of the presence of substorms for each orbit. This parameter provides an insight into whether the AE index was changing during the crossings, rather than using a threshold value, which would not necessarily inform us as to the presence of substorms, and may only indicate a high baseline value. The mean values of the standard deviation of the AE index for each group (inactive current sheet and active current sheet) are shown for each year in Figure 6. The standard error of the mean values is indicated by the vertical lines through the bars. The number of orbits in each group of Figure 6 are shown above each bar. A difference is seen between the mean values of the standard deviation of the AE index for the inactive current sheet and the active current sheet. For every year studied this parameter is higher and hence there is more variability in the AE index present during the orbits with an active current sheet. To investigate the significance of these results, we applied the Mann-Whitney-Wilcoxon test [Barlow, 1989, p. 174]. We have selected this test because it cannot be assumed that the data are normally distributed, and the Mann-Whitney-Wilcoxon test does not assume a normal distribution. However, such tests were limited due to the sometimes small sample sizes for comparison, and were not possible for 2002 or 2007. Where the test was applicable, results were statistically significant (reaching a significance level of <0.05) for all the years except in 2006.

[19] The data for 2001–2004 were combined as the orbital path varies less within these years than after 2004. A similar...
A comparison of an inactive and active current sheet was made, shown in Figure 7a. Standard errors and numbers in each group are shown for each bar. There is a significant difference between the active and inactive current sheet groups (p < 0.05). Figure 7 also shows the same comparison (also using \( \geq 5 \) crossings to define an active current sheet) for the 3 nT crossings (Figure 7b) and the 7 nT crossings (Figure 7c). Significant differences between an inactive and active current sheet are also present for both smaller (3 nT) and larger (7 nT) crossings.

The data were then grouped in a different way to further examine the influence of substorms and magnetic storms. Within each year, data were separated based on various conditions, using the values of AE and SYM-H. Quiet conditions were defined as having a standard deviation of the AE index of less than or equal to the mean value of the standard deviation (47 nT) together with a quiet ring current (minimum SYM-H > \(-50\) nT). An enhanced ring current was defined as having a minimum SYM-H value of less than \(-50\) nT. For each year, three groups were compared: quiet geomagnetic conditions (Quiet), conditions with a quiet ring current but greater than average standard deviation of the AE index (AE), and similar AE variability to the ‘AE’ group together with an enhanced ring current (RC). Figure 8 shows the mean number of 5 nT crossings for each of these groups for each year, with the standard error of the mean shown by vertical lines. The number of orbits in each group is indicated by the numbers next to each data point. Note that for years 2005–2007 there were no orbits in the RC (blue triangles) group. Out of the 128 orbits in the data set, only 6 orbits had a minimum SYM-H value of less than \(-50\) nT occurring with greater than average AE variability. When the data are divided into separate years, the numbers for comparison are therefore reduced.

However, there are two main results from Figure 8. First the mean number of crossings is larger in the groups with more AE variability (AE-red squares) than compared to quiet conditions (Quiet-black crosses) for each year studied. This result is in line with that obtained in the earlier analysis. Again statistical testing was limited due to small group sizes. However, where the Mann-Whitney test was applied, there was a significant difference between the ‘AE’ and ‘Quiet’ groups for all years except 2003 and 2006.
Secondly, data from 2001 to 2003 showed that orbits with an enhanced ring current (RC-blue triangle) had a lower mean number of crossings when compared to the conditions with a quiet ring current and high AE variability (AE-red squares). Unfortunately there were no orbits in the ‘RC’ group for the years 2005–2007. Data from 2004 show an increase in the mean number of crossings for the enhanced ring current group compared to the other groups. However, this group is based on only one orbit. Statistical tests were not possible on the ring current group due to the sample sizes.

Figure 9 shows comparison data for 2001–2004 for the 5 nT crossings (Figure 9a) as well as the 3 nT (Figure 9b) and 7 nT (Figure 9c) crossings. Again, vertical lines through each bar indicate the standard error and the number of orbits in each group is shown above each bar. Results show larger mean number of crossings for the ‘AE’ group compared to the ‘QT’ group for all sizes of crossing. The differences between the ‘QT’ and ‘AE’ groups are statistically significant. The ‘RC’ groups show a smaller mean value of crossings compared to the ‘AE’ group for all sizes of crossing, although the difference for the 7 nT data is only very small.

Our analysis shows an increased motion of the current sheet during larger than average AE variability. There is also some evidence of a reduced motion during times with an enhanced ring current in the 5 nT and 3 nT data, but the ring current has very little effect on the larger crossings (7 nT). A further method of analyzing the data was then employed, discussed in the next section.

### 3.3. Normalizing the Data

An alternative method of analyzing the data is to normalize the orbits against the amount of time spent near the current sheet. The Cluster spacecraft spent different periods of time near the current sheet due to changes in the orbital path from 2001 to 2007. By approaching the current sheet from different angles due to a combination of the orbital plane and the tilt of the current sheet, the spacecraft spent a shorter time in the current sheet when approaching from an angle along the normal to the current sheet compared to an angle away from the normal. To reduce the impact of such orbital effects, the number of crossings for each orbit was divided by the time taken for the spacecraft within each orbit to travel from +3 R_E to −4 R_E in the Z (GSM) direction. This range was chosen because it was within the region that the crossings occurred for the whole year.
database and because the spacecraft orbits crossed this region within the tail for all the years studied. We refer to this result as the normalized number of crossings per hour.

The previous section considered smaller and larger changes in $B_X$ to define a crossing and demonstrated that using a change of 5 nT in $B_X$ was a sensible criterion to use to define a crossing of the current sheet and show any effects of an enhanced ring current and substorms. In the following analysis therefore, only 5 nT crossing data are used.

Figure 10 shows the mean values of the standard deviation of the AE index for a group with lower than average normalized number of normalized crossings (<0.5 crossings per hour per orbit). The active current sheet group comprises orbits with greater than average normalized crossings (≥0.5 crossings per hour per orbit). Standard errors of the means are shown by vertical lines in the center of each bar.

![Comparison of an inactive and active current sheet](image)

**Figure 10.** Mean standard deviation of the AE index for an inactive current sheet compared to a more active current sheet, for the normalized data. The inactive current sheet group comprises orbits with less than average number of normalized crossings (<0.5 crossings per hour per orbit). The active current sheet group comprises orbits with greater than average normalized crossings (≥0.5 crossings per hour per orbit). Standard errors of the means are shown by vertical lines in the center of each bar.

The number of orbits in each group are shown above each bar. Statistical testing using the Mann-Whitney-Wilcoxon test shows significant differences (reaching a significance level of < 0.01) in the standard deviation of the AE index between the groups.

Two main methods of analysis were used to compare the orbits. Both methods considered the orbital path through the current sheet as a whole rather than studying each individual crossing of the current sheet. Our first approach was to treat each year separately. The second method involved normalizing the data in terms of its orbit, by considering the amount of time the spacecraft spent in the region under the effect of different orbital paths from year to year compared with quiet conditions (Quiet). This is statistically significant (reaching a significance level of < 0.01). The data also show that orbits with an enhanced ring current (RC) tend to have a slightly lower mean normalized crossings value compared to the ‘AE’ group, although this result was not statistically significant.

4. Discussion

Our investigation of the magnetotail current sheet surveyed Cluster 3 orbits through the region and compared geomagnetic conditions for these orbits in terms of substorms and magnetic storms.

Figure 3 showed that 46% of orbits comprised one crossing of the current sheet using a ±5 nT change in $B_Y$, suggesting a stable region for nearly half the orbits studied. However, there were many orbits with more than 1 crossing. Figure 4 showed that the mean number of crossings per year declined after 2002, which coincides with the declining phase of the solar cycle, implying that external effects may have an influence on the dynamics of the cross-tail current sheet. However, solar wind parameters prior to the crossing events have not been studied here, preventing a full investigation of the effect of external influences.

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![Comparison of current sheet under different geomagnetic conditions](image)

**Figure 11.** Mean number of crossings for different conditions for the normalized data. The group of orbits under quiet conditions (QT) have low AE variability and a quiet ring current. The group of orbits with greater than average AE variability and a quiet ring current are indicated by ‘AE’. Finally the ‘RC’ group is a group of orbits with an enhanced ring current and high AE variability. Standard errors of the means are shown by vertical lines in the center of each bar.
investigation. We also compared the size of crossings, in terms of a change in $B_y$ from $+5$ nT to $-5$ nT and similarly using $\pm 3$ nT and $\pm 7$ nT thresholds, for 2001–2004 data. [31] Our survey provided two main results. Both methods of analysis showed that the current sheet is generally more dynamic in orbits where the standard deviation of the AE index is higher. We interpret periods of large standard deviation of the AE index as having more magnetic variability due to a combination of more substorm activity and stronger substorms. The relationship with the AE index is in agreement with previous authors who studied individual crossings of the current sheet [e.g., Sergeev et al., 2006] who found a correlation of current sheet motion with the growth phase of the AE index. Our results also show that when the ring current is enhanced during magnetic storms, there is some evidence that the current sheet may be stabilized in terms of its motion for the 3 nT and 5 nT crossings, when compared to periods of substorm activity and a quiet ring current. The effect of the ring current is minimal for current sheet crossings involving a larger change in $B_y$. The difference between the larger and smaller changes in $B_y$ is not surprising and we would expect fewer crossings per orbit when considering larger changes in $B_y$. The results demonstrate that using a $\pm 5$ nT threshold in $B_y$ is appropriate for studying the effect of substorm and magnetic storm activity on the current sheet. [32] The reason for the possible ring current stabilization effect is not clear. Milan et al. [2008] previously suggested a stabilizing effect of an enhanced ring current on the magnetotail to substorm activity. We speculate that the increase in the amount of open magnetic flux in the lobes observed by Milan et al. [2008] during these periods increases the rigidity of the tail and suppresses current sheet flapping. Although the group of orbits of Cluster 3 through the current sheet which coincided with an enhanced ring current was not large in number, the damping effect was observed in the data and certainly warrants further study. [33] The aim of the study was to observe the current sheet on a global scale and as such we have not considered the tilt or thickness of the current sheet, which may have an effect on the amount of motion observed. The results of an investigation of tilt, half thickness and current density changes throughout each orbit in our database, will be the subject of a following paper. This will also provide a measure of how changeable the structure of the current sheet is under different geomagnetic conditions. In addition, the study can be extended to consider solar wind dynamic pressure changes prior to the current sheet crossings to investigate what large-scale effects can be observed within the orbits.

5. Conclusions [34] An analysis of the motion of the current sheet and the effects of substorms and magnetic storms was carried out using Cluster 3 data from 2001–2007. We found that: [35] 1. There is a decline in the mean number of crossings per year after 2002, which coincides with the decline of the solar cycle. This may suggest external influences affect current sheet motion. [36] 2. The current sheet is generally more dynamic when the AE index implies greater than average substorm activity and a quiet ring current. [37] 3. The current sheet is stabilized in terms of its smaller scale motion during periods of substorm activity when the ring current is enhanced, compared to periods of substorm activity and a quiet ring current. We propose that magnetic storms cause a rigidity of the magnetotail which inhibits current sheet motion.


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