Electromagnetic Perturbations in the Reconnecting Current Sheet in MRX

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Abstract.
Magnetic reconnection is a fundamental plasma process in which magnetic field lines break and reconnect, converting magnetic field energy into particle kinetic energy. Electromagnetic fluctuations, which may play a role in fast reconnection, are studied from both an experimental and theoretical standpoint. The waves, which are in the lower hybrid range of frequencies, may be produced by a plasma instability known as the oblique lower hybrid drift instability. When the electron drift velocity is large, the theory predicts coupling between whistler and acoustic waves in the ion frame that may lead to an instability in the vicinity of the current sheet. On the experimental side, an antenna placed in the Magnetic Reconnection Experiment (MRX) at the Princeton Plasma Physics Laboratory is used to apply perturbations, and their propagation characteristics are measured. Results from a 2mm diameter antenna indicate that any induced fluctuations are confined to the current sheet and are preferentially excited in the direction of electron flow within the layer. Preliminary data from a 2cm diameter antenna shows a wave propagating in the electron flow direction at the local electron drift velocity. Thus electron drift appears to play a crucial role in the appearance of fluctuations.

Keywords: Magnetic reconnection, electromagnetic fluctuations, oblique lower hybrid drift instability

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INTRODUCTION

Magnetic Reconnection is a fundamental process in plasma physics [1, 2] that occurs everywhere from solar flares [3, 4] to a sawtooth collapse in a tokamak [5]. One of the first models of the reconnection process, developed by Sweet and Parker in the 1950s [6, 7], models the reconnection region or current sheet as a rectangular box. The Sweet-Parker reconnection rate, derived using resistive MHD, predicts reconnection rates that are far slower than what is observed. For a solar flare, Sweet-Parker predicts a characteristic time on the order of months while the process is observed to take only minutes to hours.

Two modern models of fast reconnection have been proposed in order to account for these observations. The first is a Hall MHD treatment of the current layer [8]. The finite Lamour radius effects inherent in the Hall term lead to the demagnetization of first ions and then electrons as the magnetic field gets weaker towards the center of the current sheet. The different paths of the two species lead to a current loop which may induce an out of plane quadrapole magnetic field, a signature of the Hall effect [9].

A second explanation holds that fast reconnection is due to enhanced resistivity caused by turbulence, especially electromagnetic fluctuations in the center of the current
sheet [10, 11]. An effective resistivity $\eta^* = E/J$, defined to balance Ohm’s Law in the center of the current sheet where the magnetic field is zero [12], correlates well to the fluctuation amplitudes [13]. The fluctuations are right hand polarized and have been shown to propagate in the direction of electron flow within the current sheet at phase velocities comparable to the electron drift velocity within the layer, a feature consistent with electron whistlers [13]. Both the fluctuations and the quadrupole field have been observed in the Magnetic Reconnection Experiment (MRX) [13, 9] as well as in space observations [14, 15].

Recently efforts have been made to characterize the waves in more detail from both a theoretical and experimental standpoint. On the theoretical side, a new instability mechanism has been proposed to explain their origin [16, 17]; on the experimental side, an antenna is used to apply perturbations within the current sheet and study their propagation characteristics.

**MRX CONFIGURATION**

A schematic of the Magnetic Reconnection Experiment is shown in Figure 1. Two flux cores at either end of the device generate the plasma and drive the reconnection. During the phase of the experiment being studied, the current in the flux cores is decreased, so that field lines which encircle both flux cores break as the field is pulled back into the devices. For this reason, the process is referred to as “pull reconnection.”

The MRX coordinate system is also outlined in Figure 1. MRX is a cylindrically symmetric device with the out of plane current in the reconnection region flowing toroidally around the symmetry axis. The reconnection plane is described by the coordinates $R$ and $Z$ as illustrated in the figure. $R$ is the radial coordinate while $Z$ is the direction of the reconnecting field. Magnetic probes and other diagnostics are placed near the center of the current sheet at $Z = 0$.

![FIGURE 1. Experimental Setup in MRX [18.]](image_url)
FIGURE 2. Coordinate system (left). The reconnecting field is along \( z \), \( y \) points towards the center of the current sheet, and \( x \) is the out of plane direction. On the right is an illustration of the proposed instability mechanism described in the text. Figures from [16].

OBLIQUE LOWER HYBRID DRIFT INSTABILITY

The coordinate system of the proposed instability mechanism is illustrated on the left side of Figure 2. We work in the ion frame, at a point within the current sheet such that ions are demagnetized, but the electrons remain tied to the field lines and drift with velocity \( V_0 \). Although there are density and field gradients in the \( y \) direction, we make use of a local approximation with vanishing \( k_y \) to simplify the problem.

Now imagine an electron density perturbation, \( n \), along the \( z \) direction as shown in Figure 2. By Ampere’s Law:

\[
\frac{dB_y}{dz} = \mu_0 neV_0.
\]  

Thus the cosinusoidal perturbation \( n \) in the electron density shown in the figure leads to a sinusoidal perturbation in \( B_y \). As a result, the magnetic field line bends as illustrated, and there is now a component of \( J \times B \) pushing electrons up the perturbed density gradient in the \( z \) direction. Ions, assumed to be demagnetized, follow the electrons by the requirement of charge neutrality. As a result, the initial perturbation is amplified and the instability grows.

In general, the perturbation could be at a finite angle \( \theta \) to the reconnecting field in the \( z-x \) plane. Solving for the dispersion with a drift-kinetic formulism for electrons and unmagnetized ions, the drift between the species is found to play a key role. When \( V_0 = 0 \) two whistler and two ion acoustic modes are seen. By contrast, when a finite \( V_0 \) is added to the picture, the whistler modes are Doppler shifted. This allows for coupling between the two types of modes which takes the form of complex conjugate solutions. Thus, one of the modes is unstable and an instability is present [16].
FIGURE 3. Active perturbation hardware (left). A function generator fed through a power amplifier is used to drive the antenna. The frequency may be changed by means of adjustable capacitance in the circuit box; $2MHz$ was used in the experiments described here. Location of probes within the current sheet (right). The current sheet is represented by the area between the two solid curves.

ACTIVE PERTURBATION EXPERIMENTS

In order to experimentally test this model, a loop antenna either 2mm or 2cm in diameter is used to apply perturbations and study their propagation characteristics. The probe configuration used in the experiment is shown schematically in the right side of Figure 3. The antenna or active probe (denoted by ‘A’) is on a moveable bellows which allows it to be placed either above or below a Hodogram probe (denoted by ‘H’) which measures all three magnetic field components. The direction of electron flow within the current sheet is indicated on the figure. Two separate cases are explored with respect to the location of the probes: the “detection upstream” case in which the hodogram probe is upstream from the active probe in reference to electron flow and the “detection downstream” case in which the relative locations of the probes are reversed.

A representative shot from the detection upstream case is shown in the left panel of Figure 4. The antenna is located approximately 1cm from the hodogram probe and polarized in the out of plane (toroidal) direction. As shown in the top plot, the perturbations are turned on at $t = 260\mu s$ and turned off at $t = 290\mu s$. When the current sheet passes through the location of the probes near $t = 276\mu s$, the signal from the antenna is suppressed!

The detection downstream case is shown in the right panel of Figure 4. The antenna is the same distance from the hodogram probe toroidally as before, but due to hardware constraints is slightly offset towards $+Z$. Now when the current sheet passes through the location of the probes near $t = 276\mu s$, a perturbation grows up with the largest amplitudes seen on the in plane components ($Z$ and $R$). However, this perturbation is linearly polarized unlike the whistlers observed in previous experiments such as [13].

The 2cm antenna case is shown in Figure 5 for detection 6cm downstream and the active probe slightly offset towards $+Z$. The perturbation seen when the current sheet
FIGURE 4. 2mm antenna results: detection upstream on the left and detection downstream on the right. The three panels on each figure from top to bottom are the amplifier input in the active probe circuit, the filtered signal from the hodogram probe (from top: $Z$, $R$, and $T$ components), and the position and width of the current sheet at $z = -3$. The horizontal dashed line on the bottom plot indicates the location of the active and hodogram probes.

FIGURE 5. 2cm antenna results. See Figure 4 for a description of the left panel. On the right, the calculated phase and electron drift velocities are plotted against time. The bottom panel shows excellent matching between the two quantities for the period between $t = 283\mu s$ and $t = 297\mu s$, starting just after the current sheet passes the location of the probes.

passes through near $t = 281\mu s$ has been positively identified as a nearly circularly polarized wave propagating in the direction of electron flow within the current layer; these characteristics are similar to those of naturally occurring fluctuations [13]. Furthermore, a calculation of the phase velocity (based on both the propagation direction and the phase difference between the hodogram probe and four channel fluctuation probes located at $Z = +3cm$ and $Z = -4cm$) shows an excellent match between the phase velocity and the electron drift velocity for our example shot, as shown in the right panel of Figure 5.
DISCUSSION AND CONCLUSIONS

The 2mm antenna results show that the perturbation is carried in the direction of electron flow; from the 2cm antenna we see that one can excite a wave at the electron flow velocity in this direction. But while the larger antenna seems to more effectively couple to the MRX plasma parameters for wave launching purposes, it is comparable in scale to the width of the MRX current sheet and thus cannot be considered a localized perturbation.

On the detection side, the large spacing between the fluctuation probes is non-optimal as the phase velocity calculation is forced to assume plane wave like character over a relatively large region which is not always the case. A new probe array consisting of two variably spaced hodogram type probes would both mitigate this problem and allow for a determination of the propagation direction at two points. Comparison of the two directions would be an additional check on the plane wave assumption.

Both theory and experiment indicate that the electron drift velocity $V_0$ is a key parameter in the generation of fluctuations. However, an unambiguous case in which launched modes trigger the instability and speed up reconnection has yet to be observed experimentally. Meanwhile on the theory side saturation mechanisms that may explain this remain to be investigated. Research is also ongoing to fully characterize the phase velocity and dispersion relation of the launched modes for comparison with theory.

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REFERENCES