CMPD Final Report

Experimental Study of Current-Driven Turbulence During Magnetic Reconnection

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Magnetic reconnection is an important process in magnetized plasmas ranging from the laboratory to astrophysical scales. By enabling a change in magnetic topology, it allows the system to release magnetic energy, which is believed to be the energy source powering solar flares and magnetospheric substorms. The change in topology also enables deleterious instabilities, such as the sawtooth instability in fusion experiments, to transport plasma across the experiment's minor radius. Notably, simple estimates of the finite reconnection rate due to classical resistivity fail to explain the fast and explosive nature of reconnection observed in these systems. A major goal of reconnection research is to determine which mechanisms enable "fast" reconnection to occur.

The Grant supporting the thesis work of one MIT graduate student, William Fox, is described below. The thesis research consisted of an experimental study of the fluctuations arising during magnetic reconnection in plasmas on the Versatile Toroidal Facility (VTF) at MIT Plasma Science and Fusion Center (PSFC). A mission of the DOE Center for Multiscale Plasma Dynamics, of which this research was a small part, was to explore the coupling of microscopic and macroscopic plasma dynamics. In this vein, (microscopic) current-driven turbulence has been proposed to enhance plasma resistivity and help speed the reconnection process, thus controlling the evolution of the (macroscopic) magnetic topology. The goal of this research was to study these processes on the VTF reconnection experiment.

The VTF experiment studies magnetic reconnection in the regime of strong guide field. The machine is toroidal, with a major radius of about 1 m, and includes a large chamber volume and excellent diagnostic access. Plasmas were typically created with a burst of microwaves followed by ohmic heating, with a toroidal electric field driven by a central solenoid. An additional set of toroidal conductors inside the experiment creates an x-point and figure-8 shaped flux surfaces within the chamber volume. Reconnection and current-sheet formation is driven by quickly changing currents in the internal conductors. Previous work on this device [Egedal, et al, PRL **98,** 015003, (2007)] identified a "spontaneous" reconnection regime, where a meta-stable current sheet could be formed which would then suddenly disrupt in a burst of reconnection. The fast time-variation of the reconnection rate is a useful experimental tool, as one can easily measure within the same discharge what quantities change in concert with the rate. This work studied fluctuations arising during these spontaneous reconnection events. Generally, fluctuations were observed in the range of the lower hybrid frequency to the electron cyclotron frequency.

Fluctuations were studied using impedance-matched, high-bandwidth Langmuir probes. Strong, broadband fluctuations, with frequencies extending from near the lower-hybrid frequency [f_{LH} = $(f_{ce}f_{ci})1/2$] to the electron cyclotron frequency f_{ce} were found to arise during the reconnection events. Based on frequency and wavelength measurements, lower-hybrid waves and Trivelpiece-Gould waves were identified. The lower-hybrid waves are easiest to drive with strong perpendicular drifts or gradients which arise due to the reconnection events; an appealing possibility is strong temperature gradients. The Trivelpiece-Gould modes can result from kinetic, bump-on-tail instability of a runaway electron population energized by the reconnection events.

We also observed that the turbulence is often spiky, consisting of discrete positive-potential spikes, rather than simple broadband noise. These spikes were identified as "electron phase-space holes," a class of nonlinear solitary wave known to evolve from a strong beam-on-tail instability. Electron holes are of great interest at present as they have now also been observed in the magnetosphere, including during reconnection on both the day-side and in the magnetotail. This work was the first laboratory observation of holes arising self-consistently in plasma turbulence. (Previous laboratory work launched electron holes down narrow discharge tubes by applying voltage pulses to the cathode). We also were able to make several measurements, such as the hole size both parallel and perpendicular to the magnetic field, as well as the hole propagation velocity, which was found to be faster than the typical electron thermal speed.

Because of the likely connection of many of the observed modes to energized electrons, additional study of electron energization during the reconnection events was undertaken. For this, we constructed small energy analyzer probes, which integrated 7 grid/collector pairs in a small (1.5 cm) area. Using a grid and collector allows fast electron current to be collected while ion current to be rejected, giving a measurement of the tail electron current. We established that fast electrons (to 300 eV, the maximum bias used) were produced by magnetic reconnection. However, it was not possible to measure the electron distribution function in detail, as it was also established that often the fast electron population was not even uniform over the scale of the probe. This "filamentation" of the fast electron population itself may be interesting, however, as spatial gradients in the fast electron population may also be a source lower-hybrid waves.

Overall, these instabilities were found to be a consequence of reconnection, specifically the strong energization of electrons, leading to steep gradients in both coordinate- and velocity-space. However, it was not established that these modes had a strong feedback on the reconnection process: fluctuation power varied strongly between discharges and was observed to systematically trail the reconnection events. Finally, crude estimates (using quasi-linear theory) of the anomalous resistivity due to these modes did not appear large enough to substantially impact the reconnection process.

These points are presented in greater detail in the following attached publications:

- W. Fox, M. Porkolab, J. Egedal, N. Katz, and A. Le, "Laboratory Observation of Electron Phase-Space Holes during Magnetic Reconnection," *Phys. Rev. Lett*. **101**, 255003 (2008).
- W. Fox, M. Porkolab, J. Egedal, N. Katz, and A. Le, "Laboratory observations of electron energization and associated lower-hybrid and Trivelpiece–Gould wave turbulence during magnetic reconnection," *Phys. Plasmas* **17**, 072303, (2010).
- W. Fox, *Experimental Study of Current-Driven Turbulence During Magnetic Reconnection*, Ph.D. Thesis, MIT (2009).

Furthermore, two additional publications are in preparation, one presenting the electron hole measurements in greater detail and the other on the behavior of Langmuir probes in the GHz-frequency range.