Ion Heating and Current and Momentum Profile Relaxation During Sawtooth Crashes in the MST Reversed Field Pinch

G. Fiksel 1), A.F. Almagri 1), J.K. Anderson 1), T.M. Biewer 1), A.P. Blair 1), D.L. Brower 2), B.E. Chapman 1), D. Craig 1), D.J. Den Hartog 1), W.X. Ding 2), C.B. Forest 1), C.C. Hegna 1), R. Gatto 1), J. Goetz 1), K.J. McCollam 1), V.V. Mirnov 1), R. O'Connell 1), S.C. Prager 1), J.C. Reardon 1), J.S. Sarff 1), P.W. Terry 1), S.D. Terry 2), and MST team.

1) University of Wisconsin-Madison, WI, USA
2) Electrical Engineering Department, University of California-Los Angeles, CA, USA

email contact: gfiksel@facstaff.wisc.edu

Abstract. Robust and global phenomena associated with sawtooth crashes are studied in a reversed field pinch plasma. These phenomena are: current profile relaxation, plasma momentum profile relaxation, and anomalous ion heating. We have implemented new diagnostics to characterize these processes with good spatial and temporal resolution. The profile of the parallel current to the magnetic field (inferred via laser polarimetry) flattens after the sawtooth crash which provides the most complete evidence of plasma relaxation toward a Taylor state. At the sawtooth crash we observe transport and relaxation of both the toroidal and parallel plasma momentum. The flattening of the parallel momentum profile has been predicted by two-fluid MHD theory. The majority ion temperature is measured with the Rutherford scattering diagnostic and the minority ion temperature is measured with charge exchange recombination spectroscopy. At the sawtooth crash the ion temperature almost doubles and a significant fraction of the equilibrium magnetic field energy is transferred into the ion thermal energy.

1. Introduction

The magnetic fluctuation activity in the MST Reversed Field Pinch (RFP) is punctuated by regular, sawtooth-like bursts, during which fluctuation amplitudes rapidly increase several-fold in about 100 μsec. One of the key manifestations of these bursts is the generation of toroidal magnetic flux from an increase in the dynamo activity [1], [2]. We report on recent developments in a set of robust and global phenomena associated with these discrete events. These phenomena are: current profile relaxation (flattening), plasma momentum and flow profile relaxation, and anomalous ion heating. We also describe newly implemented diagnostics to characterize these processes with good spatial and temporal resolution.

2. Current Profile Relaxation

Current profile flattening is one of the key predictions of Taylor's relaxation theory – under an assumption of helicity conservation the plasma state with the minimum energy has a uniform $J_{||}/B$ profile. Likewise, resistive MHD simulations show that when the magnetic fluctuations are larger the current profile is flatter. The experimentally measured dynamics of current profile evolution over the sawtooth agrees with these predictions [3]. The current profile was inferred from measurements with a newly developed 11 chord, fast Faraday rotation polarimeter [4] along with a toroidal equilibrium reconstruction code with inputs from edge and core measurements of magnetic field. The edge magnetic field was measured with pickup coils and the core magnetic field was measured with a motional Stark effect

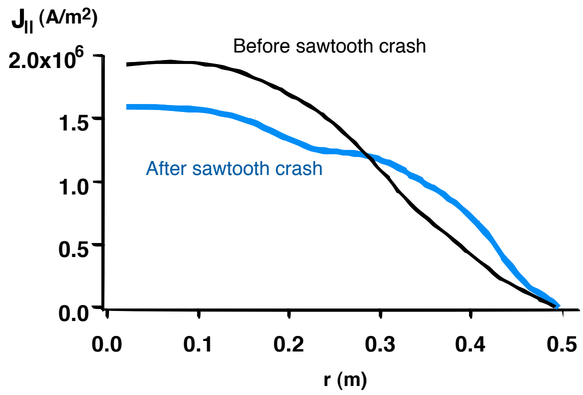

FIG. 1. Evolution of current profile over a sawtooth crash

diagnostic [5]. The flattening of the current profile (see FIG. 1) provides the most complete evidence of plasma relaxation toward a Taylor state. More detailed results can be found in D. Brower's paper EX/C4-6 in this conference proceedings. The driving force of the current relaxation is the MHD dynamo term $\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}$, where $\tilde{\mathbf{v}}$ and $\tilde{\mathbf{B}}$ are fluctuations of plasma velocity and magnetic field. Previous local dynamo measurement at the plasma edge using Langmuir probes [6] and optical Doppler spectroscopy probes [7] show good agreement between the dynamo amplitude and the edge current. Measurements in the plasma core were undertaken using chord-averaged passive Doppler spectroscopy for measurements of the plasma velocity [2] and did not provide good spatial resolutions. Measurement of local plasma velocity using active Doppler spectroscopy with diagnostic neutral beams [8] are underway.

3. Flow and Momentum Relaxation

Prior experiments have demonstrated transport of the plasma *toroidal* momentum during the sawtooth crash and provided evidence that the toroidal momentum transport is a result of non-linear mode coupling [9]. We have performed direct local measurements of the toroidal component of the non-linear MHD $\tilde{\mathbf{j}}\mathbf{x}\tilde{\mathbf{B}}$ force induced in the plasma by magnetic fluctuations.

It can be shown that the magnetic surface average of the $\tilde{\mathbf{j}}\mathbf{x}\tilde{\mathbf{B}}$ force is equivalent to the magnetic surface average of $\frac{1}{\mu_0}\frac{d}{dr}(\tilde{B}_r\tilde{B}_\phi)$, where $\tilde{B}_r$ and $\tilde{B}_\phi$ are the radial and toroidal component of the magnetic field fluctuations. This term is sometimes referred to as the magnetic Reynolds stress in analogy with the fluid Reynolds stress due to velocity fluctuations. The fluctuating components were measured at the plasma edge by an insertable magnetic coil probe. The radial derivative was approximated by finite difference between two closely spaced radial points. The result is shown in FIG. 2. The measured magnetic force density is much larger than the rate of change of the plasma momentum density. This result implies that either another large force acts on the plasma or that effects beyond single-fluid MHD are important.

A two-fluid MHD treatment of the RFP equilibrium [10] predicts relaxation of the *parallel* plasma momentum, similar to that of the parallel current. The plasma parallel flow velocity in the core is measured spectroscopically, as well as by analysis of the toroidal propagation of core resonant magnetic tearing modes. The parallel plasma velocity in the edge is measured by an insertable Mach probe. The result is shown in FIG. 3. The parallel velocity radial gradient is large away from the time of sawtooth crash, t=0, and is drastically diminished at t=0. This is consistent with the theoretical prediction.

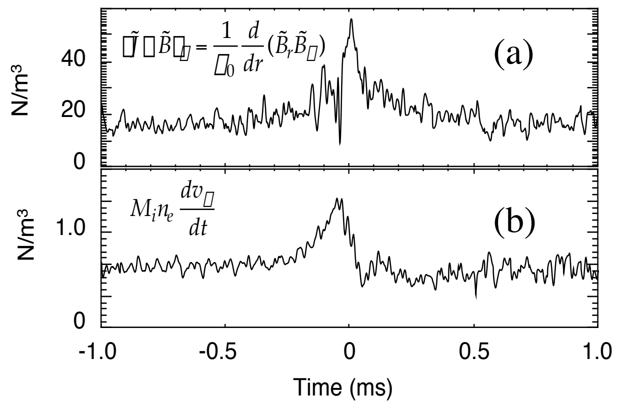

FIG. 2. Magnetic force density (a) and rate of change of plasma toroidal momentum density (b).

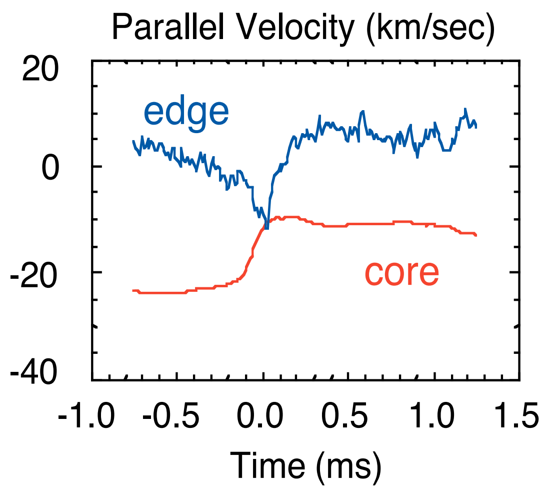

FIG. 3. Time evolution of the core and edge velocity component parallel to magnetic field.

4. Ion Heating

Ion heating at the sawtooh crash was documented previously both for majority ions via passive charge exchange measurements [11] and for minority ions via the passive Doppler spectroscopy diagnostic [12]. The spatial resolution of those measurements was poor because they represented a chord average. We have now measured the ion temperature with greatly improved spatial resolution using diagnostic neutral beams [8]. The majority ion temperature is measured with the Rutherford scattering diagnostic [8] and the minority ion temperature is measured with charge exchange recombination spectroscopy [5].

A time evolution of the ion and electron (Thomson scattering) temperatures measured at $r/a \approx 0.5$ over a sawtooth crash is shown in FIG. 4. At the sawtooth crash the ion temperature almost doubles and the ion temperature increase is observed simultaneously for all species. In addition, the increase is observed over the entire plasma cross-section indicating that it arises from a globally distributed power source. Note that the ion temperature becomes comparable to or even larger than the electron temperature, which testifies against the electron-ion collisional heating. To date, the ion heating mechanism remains unknown. The energy balance analysis reveals that a significant fraction of the equilibrium magnetic field energy, which decreases at the time of crash, is transferred into the ion thermal energy. In addition, we consistently

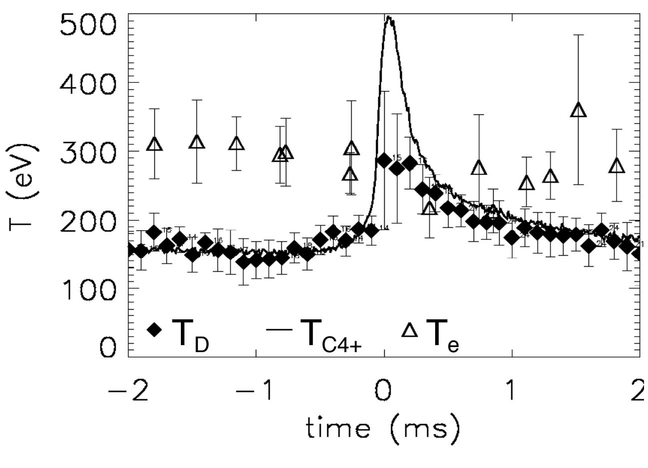

FIG. 4. Waveform of majority ion (D) temperature T_D, minority (Carbon) ion temperature (T_{C4+}), and electron temperature T_e over a sawtooth crash. Measurements are made at r/a = 0.5

observe a larger increase in the impurity temperature than the majority ion temperature. That might indicate that the heating mechanism is charge and/or mass sensitive. Plans are underway to measure the local power deposition into the ions by correlating locally measured ion current fluctuations and electric field fluctuations. The ion current will be measured by a double-sided ion current collector (Mach probe) and the electric potential will be measured with a pair of Langmuir probes.

5. Summary

Ion heating, current and momentum profile relaxation represent robust phenomena associated with sawtooth crashes in an RFP plasma. It is presumed that they result from the large change in the energy of the equilibrium magnetic field which couples to the plasma via nonlinear interaction of several fluctuation modes. It has been observed that all these phenomena, including experimentally measured 3-wave coupling term [9] always exist simultaneously and never one without each other. It remains unknown whether it is a coincidence or it is a manifestation of a still uncovered single mechanism. Studies to explain the physics responsible for these phenomena are underway.

References

[1] R.Watt and R. Nebel, Phys. Fluids **26** (1983), 1168.
[2] D.J. Den Hartog *et. al.*, Physics of Plasmas **6** (1999), 1813-1821.
[3] D.L. Brower, W.X. Ding, S.D. Terry, Phys. Rev. Letters **88** (2002), 2165.
[4] D.L. Brower, W.X. Ding, S.D. Terry, *Interior Magnetic Field Fluctuation and Profile Measurements on MST*, **Advanced Diagnostics for Magnetic and Inertial Fusion**, P.E. Stott, et al. Editors, Kluwer Academic/Plenum Publishers (New York) pgs. 407-410, 2002.
[5] D. Craig, D.J Den Hartog, and G. Fiksel, Rev. Sci. Instrum, **72** (2001), 1008-1011.
[6] H. Ji *et. al*, Phys. Rev. Letters **73** (1994), 668.
[7] P.W. Fontana *et. al*, Phys. Rev. Letters **85** (2000), 556.
[8] G. F. Abdrashitov *et. a*l., Rev. Sci. Instrum, **72** (2001), 594-597.
[9] A.K. Hansen *et. a*l., Phys. Rev. Letters **85** (2000), 3408.
[10] C.C. Hegna, Phys. Plasmas **5** (1998), 2257.
[11] E. Scime *et. al.*, Phys. Rev. Letters **68** (1992), 2165.
[12] D.J. Den Hartog and R.J. Fonck, Rev. Sci. Instrum. **65** (1994), 3238.