Measurement of Core Velocity Fluctuations and Dynamo Activity in the MST Reversed-Field Pinch

D. J. Den Hartog, J. T. Chapman[1], D. Craig, G. Fiksel, P. W. Fontana, S. C. Prager, and J. S. Sarff

Department of Physics, University of Wisconsin–Madison, 1150 University Avenue, Madison, WI 53706 U.S.A.

INTRODUCTION—Plasma flow velocity fluctuations have been spectroscopically measured in the high temperature magnetically confined plasma in the Madison Symmetric Torus (MST) Reversed-Field Pinch (RFP) [1]. These measurements show that the flow velocity fluctuations are correlated with magnetic field fluctuations such that the electromotive force $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$ is of the magnitude needed to balance parallel Ohm's law, $E_{\parallel} + \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle_{\parallel} = \eta J_{\parallel}$. This measurement is subject to limitations of spatial localization and other uncertainties, but is evidence for sustainment of the RFP magnetic field configuration by the magnetohydrodynamic (MHD) dynamo, $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$ [2]. Both the flow velocity and magnetic field fluctuations are the result of global resistive MHD modes of helicity $m = 1$, $n = 5$-10 in the core of MST.

MHD dynamo activity is large in MST during sawtooth crashes, and small otherwise. During a sawtooth crash, ion temperature increases rapidly to a level several times as high as the temperature between sawteeth, which itself can be larger than the electron temperature [3,4,5,6]. Several theories have been developed to explain this ion heating, some indicating a possible asymmetry in perpendicular to parallel heating [7,8,9]. In standard MST discharges, impurity ion temperature measured perpendicular to the magnetic field ($T_{\perp}$) is higher than impurity ion temperature parallel to the magnetic field ($T_{\parallel}$) during a sawtooth crash. Throughout the rest of the sawtooth cycle, $T_{\perp} \leq T_{\parallel}$. This is in contrast to results obtained on the EXTRAP-T2 RFP which showed the ratio of impurity ion temperature $T_{\perp}/T_{\parallel} < 1$ throughout the discharge [10].

THE MHD DYNAMO—An MHD dynamo is present in a plasma if flow field fluctuations $\tilde{\mathbf{v}}$ and magnetic field fluctuations $\tilde{\mathbf{B}}$ combine to generate $\mathbf{B}$. Using Maxwell's equations and the parallel Ohm's law shown above, the situation in the RFP is described by $\partial \mathbf{B}/\partial t = \nabla \times \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle + (\eta/\mu_0)\nabla^2 \mathbf{B}$, where the first term on the right-hand side represents the dynamo emf and the second term resistive decay of the equilibrium magnetic field configuration. In the case of the RFP, energy enters the plasma via external inductive drive of toroidal plasma current, producing poloidal magnetic flux. The dynamo emf drives parallel

[1]Present address: Siemens Medical Systems, Inc., Nuclear Medicine Group, 2501 North Barrington Road, Hoffman Estates, IL 60195, U.S.A.

current in the plasma which converts poloidal flux to toroidal flux, thus sustaining the unique reversed toroidal field configuration from which the RFP derives its name. Toroidal flux generation in the MST RFP occurs in discrete bursts often called "discrete dynamo events" or "RFP sawteeth" [11,12] (Fig. 1). Our procedure for measuring the MHD dynamo is the following [13]:

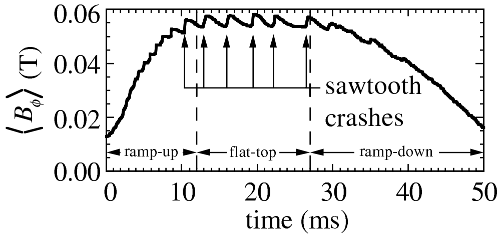

Fig. 1. The volume-averaged toroidal field of a standard low current MST discharge. Note the well-defined sawteeth during which toroidal flux is generated.

- mode resolved measurement of $\tilde{\mathbf{B}}$ with an array of magnetic pickup coils,
- spectroscopic measurement of $\tilde{\mathbf{v}}$ from toroidal, poloidal, and radial views [14],
- approximate a flux surface average by an ensemble average over sawtooth cycles,
- correlate chord-averaged $\tilde{\mathbf{v}}$ with dominant $\tilde{\mathbf{B}}$ modes to resolve the toroidal mode number n components of the dynamo product $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$.

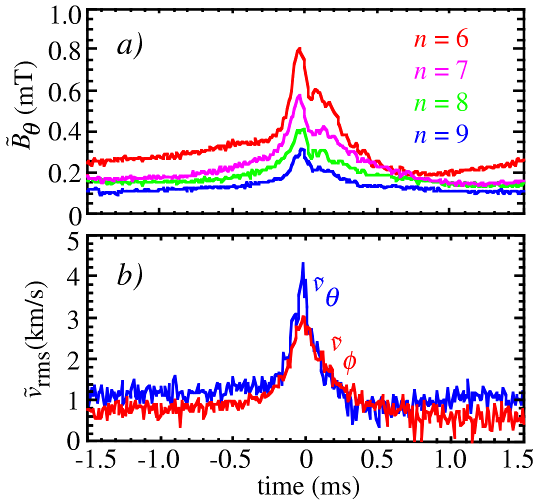

Fig. 2. Both the a) m = 1*, low* n *magnetic modes and b) rms amplitudes of the velocity fluctuations peak during the sawtooth crash at time* t = 0*.*

The fluctuation spectrum in MST is dominated by core resonant, $m = 1$, low n resistive tearing modes. The fluctuation power peaks dramatically at the sawtooth crash, as illustrated in Fig. 2 which shows measurements of $\tilde{B}_\theta$ and $\tilde{v}$ ensembled over a sawtooth window. These fluctuations are nearly stationary in the plasma frame, but rotate at 8-20 kHz in the lab frame. Both the modes and flow decelerate sharply at the sawtooth crash, and accelerate slowly following the crash [15].

As might be expected from the behavior of the magnetic and velocity fluctuations individually, the MHD dynamo product, $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$, is large at the sawtooth crash and small otherwise. Fig. 3 shows a component of the dynamo measured in the core of MST. The velocity and magnetic fluctuations reach peak coherence at the sawtooth crash and are nearly in phase, maximizing the dynamo product. When comparing the measured dynamo field to Ohm's law predictions, the dominant uncertainty is not statistical, but instead is the systematic uncertainty in the estimate of the chordal attenuation of $\tilde{v}$ and the extrapolation of

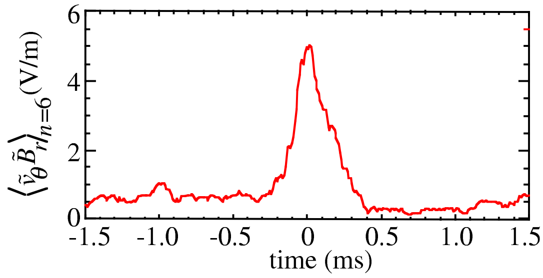

Fig. 3. The n = 6 *component of one of the measured components of* $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$.

edge $\tilde{B}$ to fluctuation amplitude in the core. The exact size of this uncertainty is impossible to calculate without prior knowledge of the fluctuation eigenfunctions, but we estimate it to be in the range of 30-50%. In spite of this difficulty, the parallel component of the measured dynamo emf is quantitatively similar to predictions calculated by Ohm's law modeling [13,16]

ANISOTROPY OF ION TEMPERATURE—Recently published measurements on the EXTRAP-T2 reversed-field pinch (RFP) show that the ratio of perpendicular to parallel impurity ion temperatures ($T_\perp / T_\parallel$) is less than one throughout the equilibrium portion of the plasma discharge. During the later period of the discharge when the amplitude of the magnetic fluctuations increases, the ratio $T_\perp / T_\parallel$ decreases substantially to $\approx \frac{1}{3}$. The decrease in $T_\perp / T_\parallel$ is brought about primarily by a large increase in parallel ion temperature as the perpendicular temperature rises only slightly. This is suggested as evidence that 'parallel viscosity' damps the perpendicular gyro-motion produced by the flow of energy from magnetohydrodynamic (MHD) fluctuations to the ions. In contrast to these results, in the MST RFP we observe $T_\perp / T_\parallel > 1$ during a sawtooth crash when MHD tearing mode fluctuations are large amplitude (Fig. 4). Both perpendicular and parallel temperatures rise sharply with no time lag visible between the two, with $T_\perp$ exhibiting a larger percentage increase than $T_\parallel$. A difference of ≈30 eV occurs during the crash as $T_\perp$ reaches ≈200 eV while $T_\parallel$ peaks at ≈170 eV. This difference persists for less than 100 μs at which point both temperatures fall together back to their equilibrium value of 80–100 eV.

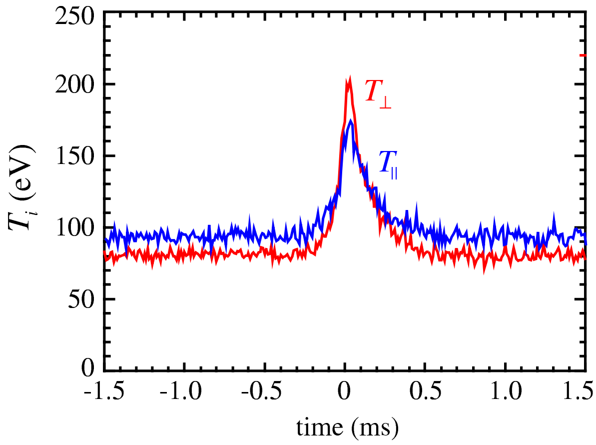

Fig. 4. Parallel and perpendicular impurity ion temperature (C v, 2271 Å) over a sawtooth cycle in MST. The two temperatures are roughly equivalent, except during the crash when perpendicular heating exceeds parallel.

Impurity ion temperature measurements in MST are made by passive chord-averaged observation of the Doppler broadened spectrum of impurity ions in a hydrogen majority plasma. Perpendicular temperature is measured with a radial viewing chord while the spectrum recorded by a toroidal viewing chord is dominated by parallel temperature [16]. As measured, the impurity ion temperature is representative of the core plasma in MST, although the toroidal viewing chord weights the core plasma more heavily relative to the edge than does the radial chord. This probably accounts for the observation that, during equilibrium away from the sawtooth crash, $T_\parallel$ is slightly larger than $T_\perp$. Previous work on MST has shown that the majority protons are also impulsively heated during a sawtooth crash [3], with no time difference between the temperature spikes recorded for the majority and impurity species. This observation, coupled with an estimated energy equilibration time between majority and impurity ions of 40 μs, implies that the behavior of the perpendicular and parallel temperatures of the majority ions is probably similar to that spectroscopically recorded for the minority ions.

The ion temperature and heating observations on MST imply that there may be an asymmetry in the ion heating mechanism, but it does not appear to be large. During the sawtooth crash, when MHD fluctuations are largest, $T_\perp$ exceeds $T_\parallel$; otherwise the two temperatures are approximately equal. Thus, any ion heating that occurs between sawtooth crashes is probably largely isotropic. Only during the crash does it appear that perpendicular heating is slightly stronger than parallel heating (or alternatively, perpendicular cooling is slightly weaker). Both perpendicular and parallel heating take place simultaneously (to within 10 μs) during that crash, implying that any energy transfer from perpendicular to parallel takes place on Alfvénic timescales. The coupling mechanism cannot simply be ion-ion coulomb collisional relaxation, as the characteristic time for that process for the majority species is 150 μs. It is important to keep in mind that the ion temperature data reported here reflect spatial averages over a scale length of approximately the minor radius a. This scale is much larger than, for example, the ion gyroradius or a magnetic island width. Thus we cannot rule out an asymmetric turbulent ion heating mechanism operating at small spatial scales. Observation of ion temperature in such small volumes awaits the implementation on MST of neutral beam diagnostic techniques such as Rutherford scattering or charge-exchange recombination spectroscopy [17].

ACKNOWLEDGEMENT—This work was supported by the U. S. Department of Energy.

[1] R. N. Dexter *et al.*, Fusion Tech. **19**, 131 (1991).
[2] S. Ortolani and D. D. Schnack, *Magnetohydrodynamics of Plasma Relaxation* (World Scientific, Singapore, 1993).
[3] Earl Scime *et al.,* Phys. Fluids B **4**, 4062 (1992).
[4] R. B. Howell and Y. Nagayama, Phys. Fluids **28**, 743 (1985).
[5] M. J. Forrest *et al.*, Rev. Sci. Instrum. **59**, 1461 (1988).
[6] T. Fujita *et al.*, Nucl. Fusion **31**, 3 (1991).
[7] C. G. Gimblett, Europhys. Lett. **11**, 541 (1990).
[8] Z. Yoshida, Nucl. Fusion **31**, 386 (1991).
[9] N. Mattor, P. W. Terry, and S. C. Prager, Comments Plasma Phys. Controlled Fusion **15**, 65 (1992).
[10] K. Sasaki *et al.,* Plasma Phys. Control. Fusion **39**, 333 (1997).
[11] R. G. Watt and R. A. Nebel, Phys. Fluids **26**, 1168 (1983).
[12] S. Hokin *et al.*, Phys. Fluids B **3**, 2241 (1991).
[13] D. J. Den Hartog *et al.*, Phys. Plasmas **6**, 1813 (1999).
[14] D. J. Den Hartog *et al.*, Fizika Plazmy **24**, 169 (1998) [Plasma Phys. Reports **24**, 148 (1998)].
[15] D. J. Den Hartog *et al.*, Phys. Plasmas **2**, 2281 (1995).
[16] J. T. Chapman, PhD thesis, University of Wisconsin—Madison, 1998.
[17] D. J. Den Hartog *et al.*, Rev. Sci. Instrum. **70**, 869 (1999).