Plasma Flow in MST: Effects of Edge Biasing and Momentum Transport from Nonlinear Magnetic Torques

J.S. Sarff, A.F. Almagri, J.K. Anderson, B.E. Chapman, D. Craig, C-S. Chiang, N.A. Crocker,
D.J. Den Hartog, G. Fiksel, A.K. Hansen, and S.C. Prager

Physics Department, University of Wisconsin
Madison, Wisconsin, 53706 U.S.A

Edge biasing in MST plasmas decreases electrostatic turbulent particle transport and increases the global particle confinement time. New Langmuir probe measurements in the edge identify decreased electric field fluctuations and increased anti-correlation of density and potential fluctuations to be responsible. Fast loss of momentum in the core of MST during sawtooth crash events can be explained as a result of nonlinear magnetic torques which allow viscous coupling over relatively distant regions of the plasma. Flow modifications resulting from biasing, plus other experiments, help reveal the nonlinear nature of this process, most directly measured by the triple product bispectral correlation between the nonlinearly interacting modes.

I. Introduction

In this paper we discuss two topics related to plasma flow in the Madison Symmetric Torus (MST) reversed field pinch [1]. The first is reduced turbulent transport resulting from the application of electrostatic biasing in the edge of MST plasmas. The RFP is a relative newcomer to the list of configurations in which flow modifications of the plasma are associated with transport reduction, hence the behavior in RFPs—similar and different—can enlighten perspectives of universal physics understanding. Key observations in MST are a reduction in the mean transverse wavenumber and near anti-correlation of density and potential fluctuations with the application of bias, suggesting the simple shear-flow paradigm [2] most often cited as the cause of reduced turbulent transport in the tokamak and other plasma configurations could be active in MST. These changes lead to a three-fold or more reduction in the electrostatic fluctuation-induced particle flux throughout the edge region, perhaps more than can be expected for the relatively modest change in the $\mathbf{E} \times \mathbf{B}$ flow-shear induced by biasing. Other affects associated with changes in the flow could be important.

The second topic relates to the dynamics of plasma flow evolution in MST. In particular, we observe a fast loss of core momentum (i.e., rotation) during sawtooth crash events. An explanation for these fast events is suggested by observations of strong nonlinear coupling occurring between tearing modes resonant in the core (with poloidal mode number m=1) and tearing modes resonant in the edge (which have m=0). This nonlinear coupling corresponds to internal nonlinear $\tilde{\mathbf{j}} \times \tilde{\mathbf{b}}$ torques acting between the modes. Viscous damping of the plasma in the vicinity of the mode-resonant surfaces provides a means to adjust the plasma flow profile on a short time scale as a result of the torques. The $m=0,1$ magnetic fluctuations involved in this process apprear in RFP dynamics in many ways, including the transport of heat and particles, as well as the “dynamo” sustainment process which maintains the reversed field in a conventional Ohmically driven RFP. Perhaps it is not surprising that they are associated with the transport of momentum as well.

The MST is one of three large RFP devices operating in the world, with minor radius $a=0.5$ m, major radius, $R=1.5$ m, and plasma current $I_p<0.5$ MA. (The other two similarly-sized RFP devices are RFX in Italy and TPE-RX in Japan.) The plasmas in Section II were operated at relatively low current to allow the insertion of probes in the edge of the plasma.

II. Turbulence Reduction with Electrostatic Biasing

Biasing of MST plasmas has been accomplished using either conventional metal electrodes or miniature plasma sources, both giving similar results. The first biasing experiments in MST were conducted with miniature plasma sources, which operate as high current emission virtual cathodes [3]. Improved particle confinement was observed, probably related to a large change in the magnitude of the flow or enhanced flow-shear (detected on a global scale). Detailed turbulence measurements were not obtained, but a reduction in floating potential fluctuations was observed, and the global particle confinement time increased ~50% [4]. Since electrostatic turbulence was known to account for the particle loss in the edge of unbiased MST plamas [5], it was reasonable to guess that the turbulent particle flux was reduced with biasing, but direct measurements of the turbulent flux were not made for technical reasons.

Using a combination of a “triple” Langmuir probe and an additional floating tip probe (in a single assembly), new detail on the turbulent behavior of biased plasmas in MST has been obtained, exhibiting features similar to those recently found in RFX biased plasmas [6]. For these new Langmuir probe studies, a metal electrode was used to bias the MST plasma (a molybdenum rod exposed to the plasma only at the tip, elsewhere insulated from the plasma by a boron nitride sleeve). The frequency spectra of the constituents of the turbulent particle flux $\Gamma = \langle \tilde{n}\tilde{E} \rangle / B$ measured at $r/a = 0.98$ are shown in Fig. 1. Despite an increase in density fluctuations, the particle flux is substantially decreased over most of the measured frequency bandwidth $f < 100\ \mathrm{kHz}$. This happens as a result of decreased transverse electric field fluctuations (reduced $\tilde{\varphi}$ and mean k_ϕ), and of near anti-correlation of the density and potential fluctuations for most frequencies, indicated by $\sin(\theta_{\tilde{n}\tilde{\varphi}})$ of the cross-correlation phase. Similar turbulent particle flux measurements have been made at several radii $r/a \geq 0.9$, all showing large transport reductions as in Fig. 1. Although these turbulence changes can be understood in terms of the shear-flow paradigm, the shear in the electric field (and hence $\mathbf{E} \times \mathbf{B}$ flow) within the edge region changes by less than a factor of two both in this and previous bias experiments in MST. We also note that electrostatic fluctuation-induced transport is *not* the dominant particle loss mechanism in the edge of biased plasmas, contrary to the case of unbiased plasmas. This follows from the fact the global particle balance confinement time is improved ~50% while the turbulent flux decreases at least three-fold. A more detailed description of these new results is in preparation and will be reported elsewhere.

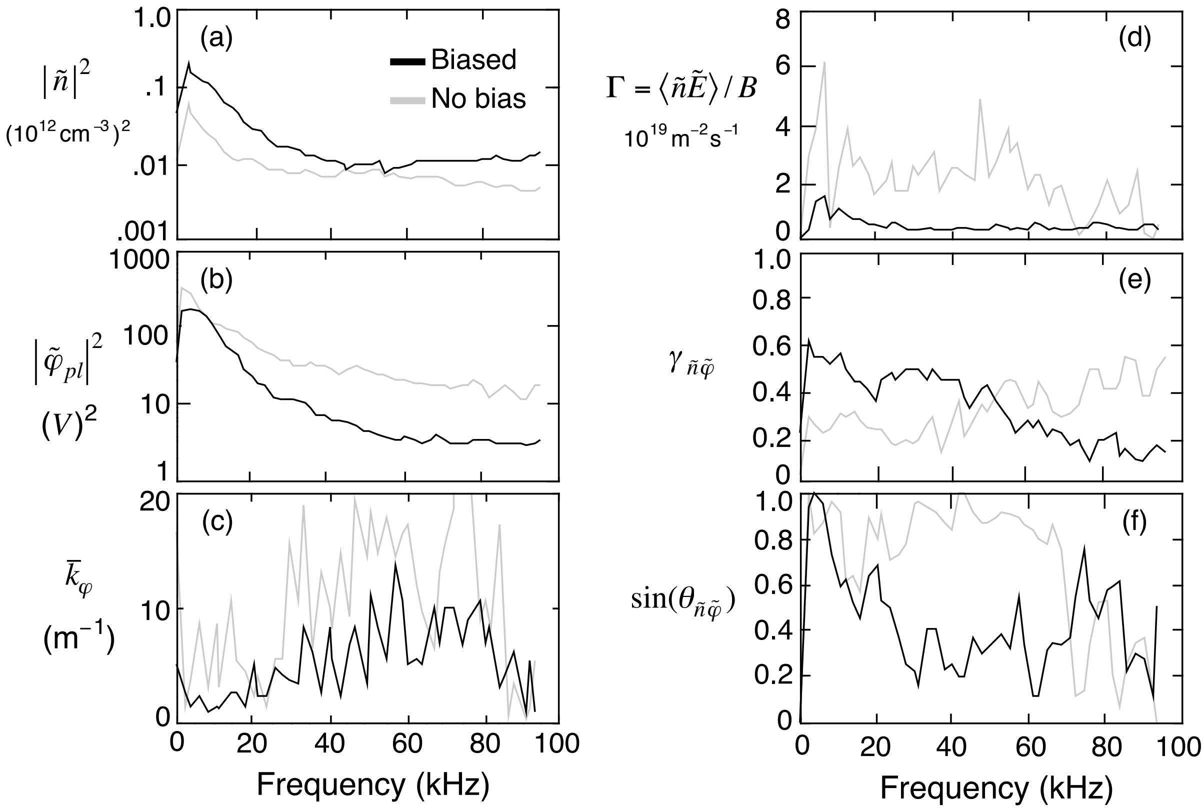

Figure 1. Frequency spectra of (a) density fluctuations, (b) plasma potential fluctuations, (c) mean toroidal wavenumber, (d) turbulent particle flux, (e) cross correlation coherence of density and potential fluctuations, and (f) sine of the cross correlation phase of density and potential fluctuations.

III. Nonlinear Magnetic Torques

Plasmas in MST exhibit sawtooth oscillations [7] with features similar to those observed in tokamaks. A unique feature of the sawtooth in an RFP is that positive toroidal flux is generated in the abrupt "crash" phase by magnetic reconnection, which replenishes the resisitive decay that occurs in the "ramp" phase. This sawtoothing of the toroidal flux reflects the dynamo mechanism operating in MST, and the underlying MHD magnetic turbulent dynamics. Several other notable changes in the plasma occur during the fast ~100 μs crash phase, one of which is the nearly complete loss of momentum (rotation) in the core of the plasma in a time about two orders of magnitude faster than classical collisional can produce.

Evidence suggests this fast momentum loss results from nonlinear magnetic torques operating between tearing modes resonant in the core and edge [8]. In MST, the plasma flow in the vicinity of a mode's resonant surface is seen to be strongly coupled to the mode, i.e., the mode and plasma co-rotate. Hence torques acting between the modes allow viscous coupling across relatively distant regions in the plasma.

Several experimental observations support this nonlinear torque hypothesis. First, and most directly, a nonlinear Lorentz force $\langle \tilde{\mathbf{j}}_{\mathbf{k}} \times \tilde{\mathbf{b}}_{\mathbf{k}} \rangle$ (and an associated torque) results on a magnetic surface where mode $\mathbf{k}$ is resonant with the mean field ($\mathbf{k} \cdot \mathbf{B} = 0$) when the current density fluctuation $\tilde{\mathbf{j}}_{\mathbf{k}}$ is produced by the nonlinear coupling of $\mathbf{k}$ with two other modes satisfying the three-wave sum rule $\mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2$. The magnitude of the nonlinearly generated current density will be related to the fluctuation amplitudes of the coupled modes $j_k \sim b_{k_1} b_{k_2}$, hence the magnitude of the nonlinear force (and torque) is proportional to the correlated triple product $\langle b_k b_{k_2} b_{k_3} \rangle$ averaged over a flux surface. Note that this is essentially the magnetic bispectrum. Also note that these torques are "internal" (produce no net torque), so their main effect is to redistribute momentum by tending to flatten the momentum profile. The absolute magnitude of the torque depends on nonlinear coupling coefficients associated with overlap integrals of the spatial eigenfunctions of the involved modes [9,10], not easily measured. However, the bicoherence of three modes is detectable. Examples are shown in Fig. 2 for the largest expected three-wave interactions associated with the dominant mode m=1, n=6 in the core of MST. The key feature of these data is that the correlated triple products (Fig. 2b) peak sharply near the sawtooth crash (t = 0 in this ensemble of sawtooth events) and vanish away from the crash. This results from the peaking of the magnetic fluctuation amplitudes at the crash, and from the phase locking of the modes at the crash. Phase locking in this way is the hallmark feature of nonlinear coupling.

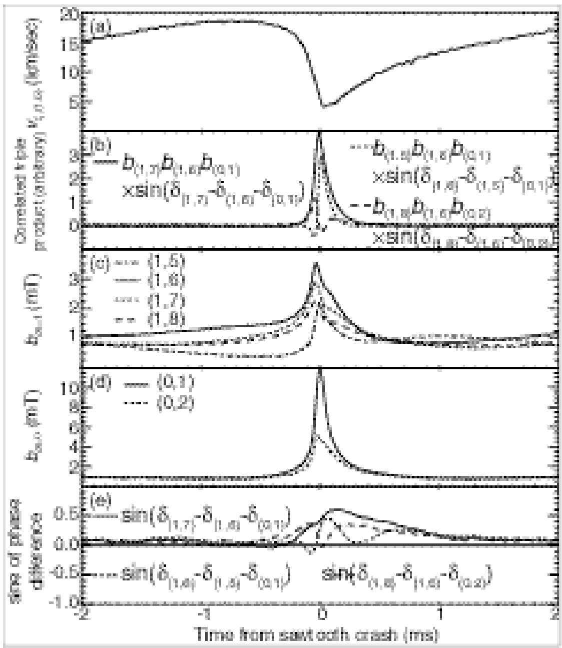

Figure 2. (a) Toroidal phase velocity of m=1, n=6 core mode, (b) dominant nonlinear triple products involving m=1, n=6 mode, (c) m=1 mode amplitudes, (d) m=0 mode amplitudes, (e) phase factors.

A second experiment directly tests the nonlinear nature of the torque by removing one of the coupled modes from the system. In this case, the m=0 mode is easily removed by operating the plasma not as an RFP, but with safety factor $q(a) > 0$. The m=0 mode is resonant at the q=0 surface, so such operation removes its resonant surface from the plasma. The experiment is done such that, during the course of a single dischage, $q(a)$ is increased from zero to a small but finite positive value. A typical result is shown in Fig. 3. The usual sharp decreases in the n=6 mode phase velocity at sawtooth crash events, which persist with $q(a) = 0$, vanish when $q(a) > 0$, even though the m=1 mode amplitudes continue to sawtooth. Other evidence of the nonlinear nature of these torques is seen when a non-rotating external n=6 magnetic perturbation is applied to the plasma and (linearly) couples to the plasma-generated n=6 mode. As expected, the n=6 mode ceases rotation as it locks to the magnetic perturbation (i.e., field error), but in addition, *all* of the core modes cease rotation as well.

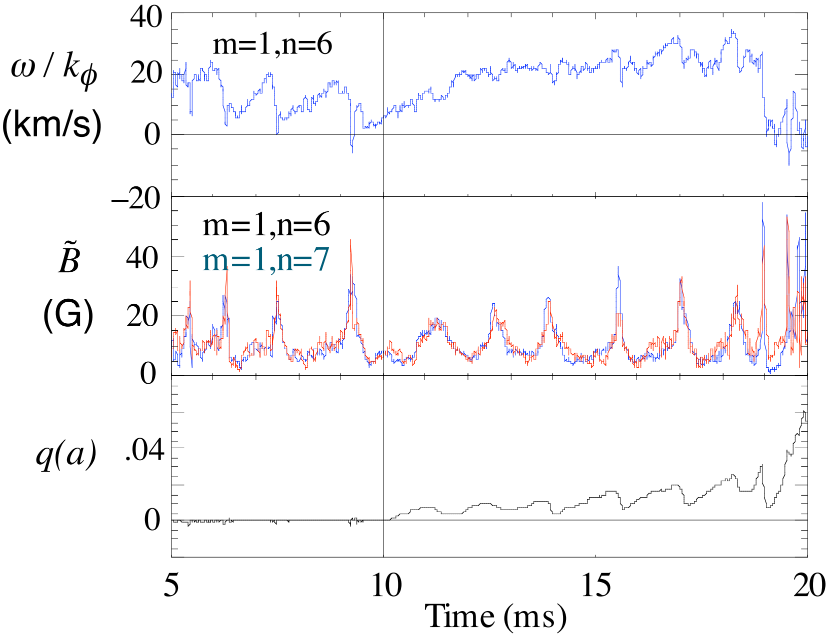

Figure 3. Top panel shows the m=1, n=6 mode phase velocity. The middle panel shows the m=1, n=6 & 7 core-resonant mode amplitudes. The bottom panel shows the safety factor. At 10 ms, the plasma transitions to $q(a) > 0$ *and the m=0 surface is removed from the plasma.*

References

1. R.N. Dexter et al., Fusion Technol. **19**, 131 (1991).
2. P.W. Terry, Rev. Mod. Physics **72**, 109 (2000).
3. D. Craig et al., Phys. Rev. Lett. **79**, 1865 (1997).
4. The two-fold improvement in global particle confinement reported in ref. 3 was later discovered to be too large as a result of non-axisymmetries in H_α measurements.
5. T.D. Rempel et al., Phys. Fluids B **4**, 2136 (1992).
6. V. Antoni et al., Plasma Phys. Control. Fusion **42**, 83 (2000).
7. S. Hokin et al., Phys. Fluids B **3**, 2241 (1991).
8. A.K. Hansen et al., submitted to *Physical Review Letters*
9. C.C. Hegna, Phys. Plasmas **3**, 4646 (1996).
10. R. Fitzpatrick, Phys. Plasmas **6**, 1168 (1999).