New Observations Concerning the Origin and Consequences of MHD Activity in the MST Reversed Field Pinch

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Abstract. Reversed Field Pinch (RFP) plasmas exhibit a broad spectrum of MHD activity. The instability underlying much of this activity in the standard RFP discharge has been identified as resistive tearing and is well modelled by nonlinear, resistive MHD. In recent years two additional types of discharge have been produced: those with reduced tearing activity leading to improved confinement and those with one large mode termed Quasi-Single Helicity (QSH). Our understanding of MHD activity and its consequences in all three plasma types is incomplete. In this paper, we present new data concerning (1) the origin of m=0 modes in standard plasmas, (2) the MHD dynamo in QSH plasmas, (3) the effect of MHD modes on plasma rotation, and (4) the achievement of a nearly dynamo-free RFP plasma.

1. Introduction

Reversed Field Pinch (RFP) plasmas are strongly affected by a broad spectrum of MHD activity. In standard RFP discharges driven by toroidal induction, resistive tearing modes account for much of this activity and have been well modelled by nonlinear, resistive MHD computation.[1] One prediction of this modelling is that modes with poloidal mode number m=0 should be linearly stable and yet still be excited through nonlinear mode coupling to m=1 modes. In this paper we show direct measurements of the m=0 linear drive terms in MHD which confirm this picture during the standard sawtooth crash in the Madison Symmetric Torus (MST) experiment.[2] Recently, it has also been observed that during some discharges, one m=1 mode will spontaneously grow to large amplitude, dominating the magnetic spectrum.[3] These plasmas, referred to as Quasi-Single Helicity (QSH) are somewhat intermediate between the standard multiple helicity state, in which there exist many modes of comparable amplitude, and a theoretical Single Helicity state [4] in which all modes vanish except one. Here we present measurements of the MHD dynamo in QSH plasmas which show that the dynamo spectrum, like the magnetic spectrum, becomes dominated by a single mode.[5] The appearance of one large mode in QSH plasmas has also enabled a detailed examination of the torques induced on the plasma by mode-induced eddy currents in the conducting wall surrounding the plasma. During QSH periods, the mode rotation is observed to decrease slowly and the deceleration is in good agreement with a theory based on wall eddy currents.[6] Finally, we also demonstrate the achievement of a nearly dynamo-free RFP plasma.[7] This is accomplished by programming the applied toroidal and poloidal inductive electric fields to more directly drive the needed current profile in the RFP. As a result, MHD activity is reduced and the dynamo terms that result are decreased to the point that they no longer dominate in Ohm's law.

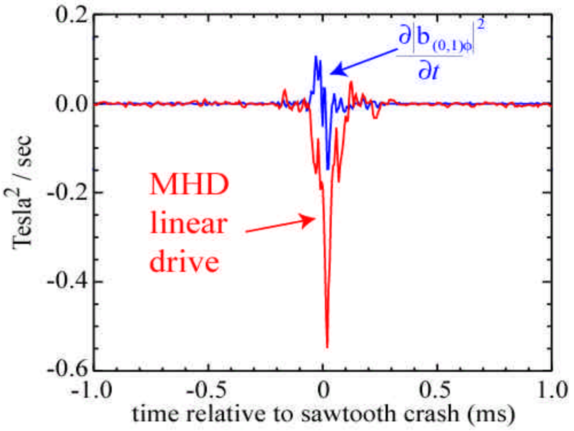

FIG. 1. The average MHD linear drive term for the m=0, n=1 toroidal magnetic component as measured in the edge of MST is shown versus time. The left hand side of Eq. 1 is also shown.

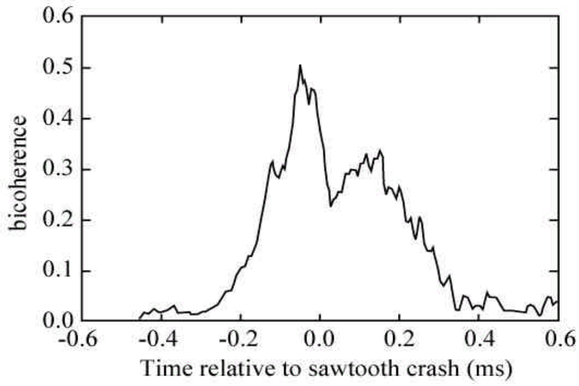

FIG. 2. The bicoherence between magnetic fluctuations with (m,n) = (0,1), (1,6), and (1,7) versus time indicating nonlinear coupling during the sawtooth crash (t=0) in MST.

2. Measurements of m=0 mode origin in standard RFP plasmas

In standard RFP plasmas, theory predicts that m=0 modes are linearly stable but should appear at finite amplitude as the result of nonlinear coupling between pairs of unstable m=1 modes.[1,8] As such, they play a key role in broadening and saturating the m=1 spectrum which can in turn strongly impact confinement. In MST, we have now directly measured the linear MHD drive term for m=0 modes in the plasma edge. The MHD equation for the evolution of the m=0, n=1 magnetic mode energy is

$$\frac{\partial\left|b_{(0,1)j}\right|^2}{\partial t} = \left\langle\left(\nabla\times\left(\mathbf{v}_{(0,1)}\times\mathbf{b}_{(0,0)}\right)\right)\cdot\mathbf{b}^*_{(0,1)j}\right\rangle + C.C. + nonlinear + dissipation \tag{1}$$

where b is the magnetic field, v in the velocity, (0,1) and (0,0) refer to the (m,n) Fourier terms, j is the vector component, and < > indicates an average over a magnetic surface. The first term and its complex conjugate on the right hand side of Eq. 1 correspond to the linear drive for the m=0 mode. If this linear drive is positive, the mode is gaining energy from the equilibrium (0,0) fields and hence is unstable. If the linear drive is negative, the mode is losing energy to the equilibrium fields and is stable. We have measured the linear drive directly in the edge of MST using magnetic probes and Langmuir probes to infer the velocity from E×B. The Fourier components are obtained by correlating the single point probe measurements with Fourier resolved magnetic measurements at the plasma boundary. FIG. 1 shows the linear drive for the toroidal component of the m=0, n=1 mode throughout a sawtooth crash during which m=0 modes burst strongly. The derivative of the mode energy (left hand side of Eq. 1) is also shown in FIG. 1. The linear drive is negative throughout the sawtooth crash indicating that the growth of the mode is not due to linear instability.

To test whether nonlinear mode coupling may be responsible for the m=0 mode growth, we have measured the bicoherence between m=0 and m=1 modes in these plasmas. Previous measurements of nonlinear mode coupling serve as a guide for which particular mode interactions to consider here.[9,10] The largest triplet interaction is expected to be between the (0,1), (1,6), and (1,7) modes. The bicoherence for this interaction is shown in FIG. 2. The presence of a large bicoherence indicates that nonlinear coupling is indeed occurring although the direction of energy flow cannot be determined from this measurement alone. These results

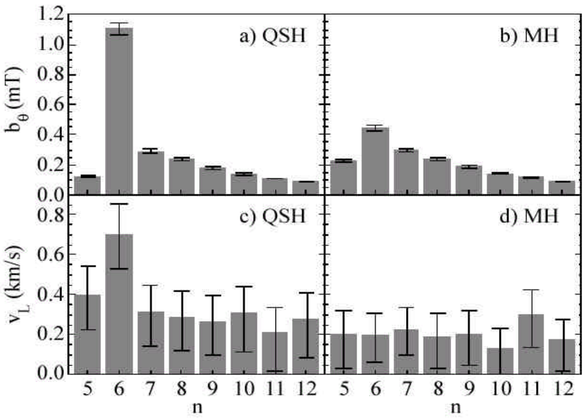

FIG. 3. Measured toroidal mode number spectra for magnetic field fluctuations (a and b) and the line-integrated velocity fluctuations (c and d) during QSH and MH plasmas.

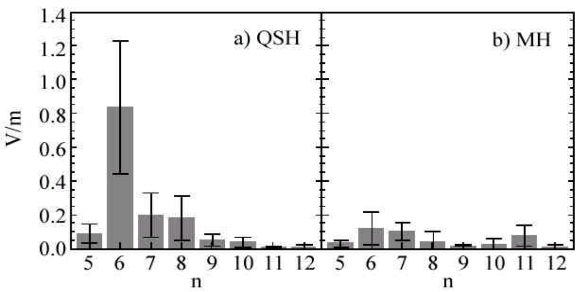

FIG. 4. Toroidal component of MHD dynamo inferred from line-averaged velocity measurements and edge magnetic measurements in a) QSH and b) MH plasmas.

are in good agreement with nonlinear, resistive MHD computation which predicts that m=0 modes should be linearly stable but excited by nonlinear coupling with m=1 modes. Future measurements will be aimed at direct measurement of the nonlinear power flow between m=1 and m=0 modes.

3. MHD dynamo measurements during Quasi-Single Helicity periods

In QSH plasmas, one m=1 mode grows to large amplitude and dominates all others in the magnetic fluctuation spectrum. It has been suggested that these plasmas may be the precursor to a pure single helicity RFP state in which all modes vanish except a single m=1 mode which maintains the field-aligned current profile by a more laminar MHD dynamo.[3,4] An important question is whether in QSH plasmas, the dynamo becomes dominated by one mode or remains multi-mode in character. We have used passive Doppler spectroscopy [11,12] to measure the radial and poloidal velocity fluctuations in QSH plasmas. We find that the velocity fluctuations become dominated by one mode just as the magnetic fluctuations do and that the mode number matches that of the dominant magnetic mode. This is demonstrated in FIG. 3 which shows the magnetic and velocity fluctuation mode spectra during standard multi-helicity plasmas and in QSH plasmas. The magnetic mode spectra are obtained from Fourier analysis of an array of magnetic coils at the plasma boundary. The velocity mode spectra are obtained by correlating passive Doppler measurements with the magnetic modes measured by the coil array. We note that the velocity mode spectrum is not as strongly peaked as the magnetic mode spectrum but is still dominated by one mode nonetheless.

We have also examined the phase of the velocity fluctuations relative to that of the magnetic fluctuations. Indeed the two combine to produce strong MHD dynamo terms of the form <**v**´ **B**>, where < > denotes a flux surface average. The toroidal component of the MHD dynamo has been measured and is shown in FIG. 4. Clearly this portion of the dynamo does appear to be more concentrated in one mode during QSH plasmas. The narrowness of the dynamo product comes primarily from the peaked magnetic spectrum although the velocity spectrum contributes to this as well. New techniques are being developed to measure the remaining terms contributing to the total dynamo product and to better localize the measurements in space.

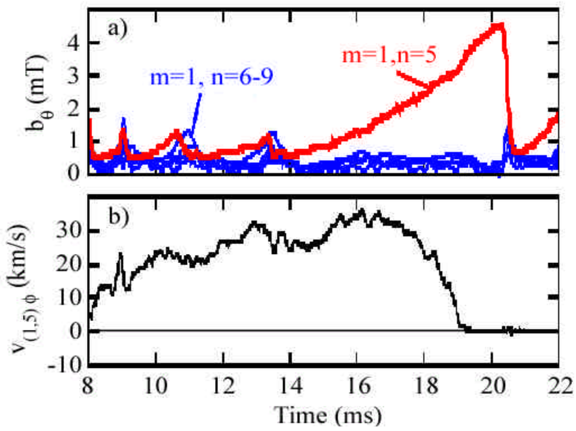

FIG. 5. a) Magnetic mode amplitudes for several m=1 modes and b) toroidal rotation for the dominant mode during a long QSH period.

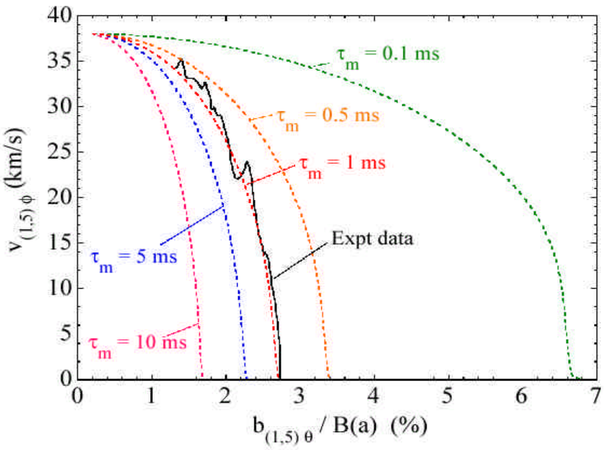

FIG. 6. Mode braking curves based on the wall eddy current model for several momentum confinement times along with the experimentally measured curve.

4. Mode braking due to eddy currents induced in the conducting shell

A common observation during QSH plasmas is that the plasma rotation gradually slows as the dominant mode amplitude increases. This effect is demonstrated in FIG. 5. The gradual slowing of the plasma is well described in MST by a model that attributes the braking to eddy currents induced by the mode in the conducting shell surrounding the plasma.[6] In this model, the rotating mode induces eddy currents in the shell which are slightly phase-shifted due to the finite resistivity and inductance of the shell. These phase-shifted currents produce a secondary response at the mode resonant surface resulting in a fluctuating current. The fluctuating current interacts with the magnetic fluctuation to induce a $\langle \mathbf{j} \times \mathbf{b} \rangle$ force near the mode resonant surface which slows the mode down. This change in momentum is then coupled to the bulk plasma by viscous or other processes and the whole plasma rotation slows. The fully quantitative, dynamical model predicts a "braking curve" which relates the mode rotation speed to the mode amplitude. The model has one remaining free parameter which is the global momentum confinement timescale. Braking curves predicted by the model for various momentum confinement times are shown in FIG. 6. The curves overlay those measured experimentally for values of the momentum confinement time ~ 1 ms. This value matches the empirical value determined from transient experiments using biased probes in the edge of the plasma.[13] Thus, the evolution of the mode and plasma rotation is consistent with the effects of wall eddy currents. The present analysis is one of the most detailed to date of this effect which is important not only for the RFP but for any plasma surrounded by conducting structures.

5. Nearly dynamo free RFP plasmas

A longstanding goal for the RFP has been to produce plasmas in which the current profile is everywhere driven directly by externally applied power. In this case, the fluctuation-driven dynamo in the standard RFP powered by toroidal induction would be unnecessary and the thermal transport caused by the associated magnetic turbulence would be minimized. Earlier studies in MST [14-16] and elsewhere [17-19] have shown that confinement can be increased up to tenfold by inductive modifications to the current profile which reduce the magnetic fluctuations. We now have examined the profile of mean field Ohm's law in these plasmas. This analysis has only recently become possible due to advances in magnetic field (current profile) measurements and equilibrium reconstruction. The magnetic field profiles are constrained by 11

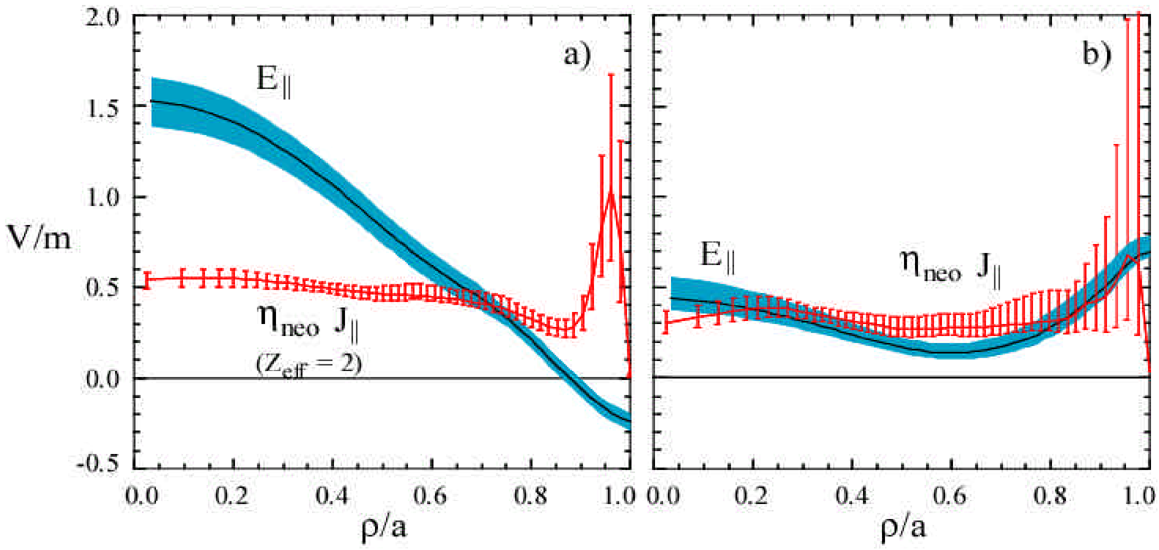

FIG. 7. Reconstructions of the terms in Ohm's law parallel to the mean magnetic field for a) standard RFP plasmas between sawtooth crashes and b) improved confinement plasmas with modified toroidal and poloidal inductive programming.

chords of FIR Faraday Rotation [20] (which measure the poloidal magnetic field profile) and a measurement of the toroidal magnetic field on the plasma axis by Motional Stark Effect [21] (which contrains the total poloidal current in the plasma). The inductive electric field is computed using the time-derivative of the Grad-Shafranov equation.[7] In standard RFP plasmas driven purely by toroidal induction, we find that $E \neq \eta J$ as shown in FIG. 7a. The difference between E and ηJ is accounted for by dynamo terms in Ohm's law. In improved confinement plasmas where poloidal and toroidal inductive electric fields are tailored to better drive current in the edge of the plasma, we find that magnetic fluctuations are suppressed and $E \approx \eta J$. This implies that the dynamo is suppressed and that the required currents are being more directly driven by the applied power. Development of more precise and steady state current profile control in the form of RF waves is underway.

6. Summary

In this paper, we have presented new measurements of several MHD characteristics in RFP plasmas. First, the origin of m=0 modes has been probed by direct measurement of the linear MHD drive terms in the edge which indicate that the modes are stable. The presence of strong bicoherence with m=1 modes supports the picture of these modes being driven primarily by nonlinear coupling. First measurements of the MHD dynamo in QSH plasmas indicate that it is more concentrated in one mode, as is the magnetic fluctuation spectrum. Improvements to diagnostics are underway to measure the spatial distribution and acquire all vector components of the dynamo. During QSH plasmas, the toroidal rotation gradually slows, consistent with drag from mode-induced eddy currents in the conducting shell surrounding the plasma. Finally, improved internal measurements of magnetic profiles and a novel reconstruction technique have allowed us to measure the terms in Ohm's law and quantify the amount and spatial distribution of the dynamo in standard plasmas. With modified inductive poloidal and toroidal electric field programming, fluctuations can be reduced, confinement improved, and the dynamo suppressed.

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