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PLASMA ROTATION, DYNAMO, AND NONLINEAR COUPLING IN THE REVERSED FIELD PINCH

S.C. Prager, A.F. Almagri, M. Cekic, J. Chapman, D.J. Den Hartog,
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J.R. Drake*, S. Mazur*, P. Norlund*, and H.E. Saetherblom*

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Plasma rotation, dynamo, and nonlinear coupling in the reversed field pinch

S C Prager, A F Almagri, M Cekic, J Chapman, D J Den Hartog, G Fiksel, C Hegna, H Ji and J S Sarff

Department of Physics, University of Wisconsin, Madison, WI 53706
USA

J R Drake, S Mazur, P Nordlund and H E Saetherblom

Division of Fusion Plasma Physics (Association EUROTAM-NFR),
Alfven Laboratory, Royal Institute of Technology, S-100 44 Stockholm

Abstract. Two important effects of MHD fluctuations in the RFP and tokamak are current generation (the dynamo effect) and mode locking. In the T1 and MST RFP experiments new results reveal the mode dynamics underlying these phenomena. In T1 the effect of specific magnetic Fourier modes on the current density profile is evident. In MST, the MHD dynamo term ($\delta \mathbf{v} \times \delta \mathbf{B}$) is measured in the plasma edge, and found to account for the time dependence of the edge current throughout a sawtooth cycle. As edge resistivity is increased in T1 the fluctuation amplitude increases to maintain the dynamo-driven current, as expected from MHD computation. The modes responsible for the dynamo often lock to the local magnetic field error at the vertical cut in MST. The plasma rotation velocity has been measured with a fast Doppler spectrometer to a time resolution of 1 μs. The plasma rotation and mode phase velocity are remarkably well-correlated, with both slowing, in the presence of an impulsive field error, in a 100 μs timescale.

1. Introduction

In the reversed field pinch (RFP), magnetic fluctuations have enormous effect on plasma behavior. In this paper we focus upon two effects, both likely understood from MHD theory - the influence of magnetic fluctuations on the current density profile and the effect on plasma rotation. Both of these phenomena are of importance in other configurations, such as the tokamak. However, in the RFP these effects are large, so that the underlying physics mechanisms can be effectively studied.

We report new results from the MST and T1 reversed field pinch experiments. MST, at the University of Wisconsin, is a large plasma ($a = 0.5$ m, $R = 1.5$ m) with moderate plasma current ($I \approx 0.5$ MA), modest current density and aspect ratio of 3. T1 at the Royal Institute of Technology in Stockholm is a small RFP ($a = 6$ cm, $R = 0.5$ m, $I \approx 40$ - 100 kA) with high current density (10 MA/m^2) and aspect ratio of 8.8. Observation of consistent effects in both devices supports the generality of the MHD interpretation of the experimental results.

The influence of magnetic fluctuations on the current density profile, or magnetic field generation, is known as the dynamo effect. In addition to astrophysical and RFP plasmas, the dynamo can also modify the current density profile in a tokamak in the presence of tearing modes (Mirnov oscillations), and perhaps sawteeth and disruptions. Three new observations support the MHD model of the dynamo. First, the current density profile is observed to change in correlation with specific magnetic Fourier modes (in T1). The profile of the normalized current density ($j_{\|}/B$) is, at times, observed to be hollow within the resonant surface of the dominant mode; in addition, flattening of the current profile occurs at the resonant surface of the $m = 0$ mode, where m is the poloidal mode number. Second, the MHD dynamo term $\delta \mathbf{v} \times \delta \mathbf{B}$ is measured in the edge with probes (inferring the fluctuating flow velocity from the measured $\delta \mathbf{E} \times \mathbf{B}$ in MST). We find that the MHD dynamo can account for the plasma current in a time-dependent fashion, throughout a sawtooth cycle. Third, the variation of magnetic fluctuations with edge resistivity in T1 is as predicted by MHD computation, i.e., the magnetic fluctuations increase with edge resistivity so as to continue to drive the required edge current.

In MST, new information on the dynamics of mode locking has been obtained since (1) a sawtooth crash generates an impulsive field error (with a 100 μs risetime), initiating a time sequence of events which permits the study of plasma rotation and mode locking dynamics in a manner not possible in steady state, and (2) a Doppler spectrometer has been developed which measures plasma flow with 1 μs resolution. The magnetic modes lock to the sudden field error, followed by sudden deceleration of the plasma rotation within 100 μs. The plasma decelerates in a time consistent with that expected from the magnetic braking force of the field error. Thereafter, the error subsides, and the plasma and mode reaccelerate in several ms, consistent with a particle confinement time, which is interpreted as the time for the radial electric field to re-establish. Interestingly, during deceleration the mode leads the plasma, but during acceleration the plasma leads the mode.

In the RFP, there are several dominant magnetic modes which are phase-locked together. In Section II, we present some new evidence from T1 for strong coupling between the dominant modes. We then present results on the dynamo (Section III) and plasma rotation and mode locking (Section IV).

2. Mode coupling

In the RFP, the magnetic fluctuation spectrum is known, from both experiment and MHD computation, to peak at $m = 1$ and toroidal mode number $n \approx 2R/a$. The n-spectrum is dominated by modes about equal in number to the aspect ratio. For example, in T1 typically the n spectrum peaks at $n \approx 15$, with a width of about 6, as shown in figure 1a. By contrast, in MST, with an aspect ratio one-third that of T1, the fluctuation spectrum is dominated by modes in the range $n = 5 - 8$.

The large modes are coupled to each other by three wave interactions satisfying the relations $n_3 = n_1 + n_2$, $m_3 = m_1 + m_2$. Thus, it might be expected that the dominant $m = 1$ modes would be coupled by $m = 0$, $n = 1$ modes. Indeed, the n-spectrum of the $m = 0$ mode typically peaks at $n = 1$ (figure 1b) [1]. At times, the n spectrum splits into two peaks, as shown in figure 2a [2]. The separation between the two peaks is $\Delta n = 4$. Simultaneous with the appearance of the two peaks (in the $m = 1$ n-spectrum) there arises a large $n = 4$ peak in the n-spectrum of the $m = 0$ mode, as shown in figure 2b, providing strong evidence for the role of $m = 0$ in coupling the $m = 1$ modes.

3. The dynamo effect

The mean-field parallel Ohm's law can be expressed as [3]

$$\langle E_{\|} \rangle - \eta \langle j_{\|} \rangle = \frac{\langle \delta \mathbf{E}_{\perp} \cdot \delta \mathbf{B}_{\perp} \rangle}{B} + \frac{\langle \nabla_{\perp} \delta \, \mathbf{p_e} \cdot \delta \mathbf{B}_{\perp} \rangle}{ne} \tag{1}$$

where <> denotes an ensemble (or flux-surface) average and δ denote fluctuating quantities. There are two current-generating dynamo terms on the right hand side. The first term represents the usual contribution to the $\delta \mathbf{v} \times \delta \mathbf{B}$ dynamo from the fluctuating $\mathbf{E} \times \mathbf{B}$ drift ($\delta \mathbf{E} \times \mathbf{B}$). The second term is a finite pressure contribution which arises from the p_e term in Ohm's law, and can be viewed as the contribution to the $\delta \mathbf{v} \times \delta \mathbf{B}$ term from the fluctuating electron diamagnetic drift.

Both dynamo terms have been measured in the edge of MST using Langmuir probes. The sawtooth crash in the RFP represents a discrete dynamo event in which the toroidal magnetic flux is suddenly generated, while the edge toroidal field becomes more negative. The sudden generation in toroidal flux, Φ, is illustrated in figure 3 (bottom trace) which displays the one-turn poloidal surface voltage $V = d\Phi/dt$. The two components of $<\delta \mathbf{E}_\perp \cdot \delta \mathbf{B}_\perp>$ (the two top traces) increase simultaneous with the flux generation. However, the increase in the edge parallel plasma current, j_p, (measured with a small movable Rogowski coil) is delayed in time.

If we consider the inductive change in the parallel electric field, then we observe that the pressureless MHD dynamo (the first term in eqn (1)) can account for the edge current, both during and between sawtooth crashes. The time dependence of the first three terms in Ohm's law is shown in figure 4, for one sawtooth cycle. The electric field is obtained from the measured change in the toroidal flux. The finite pressure term (or "diamagnetic dynamo") is small in MST. (Recent data in the TPE1RM-20 RFP experiment shows that at high collisionality the diamagnetic dynamo becomes large [4], perhaps consistent with earlier data in the REPUTE RFP [5]).

Correlation of the dynamo with specific magnetic modes was found in T1 through the measurement of the current density profile with insertable magnetic probes [2]. For example, the profile of $j_{||}/B$ for a time in which the m = 1, n = 17 mode happens to be particularly large is shown in figure 5a. It is notable that the profile becomes hollow within the location of the resonant surface. For the more general case, in which many modes are large, the $j_{||}/B$ profile is also often hollow (or flat) within the resonant surfaces of the dominant modes, as seen in figure 5b. Moreover, a flattening (or inflection point) in the profile is evident at the location of the m = 0 resonant surface, indicative of the local effect of the m = 0 mode on the current profile.

If the fluctuations serve to drive the edge current, it might be expected that the magnitude of the fluctuations would depend upon the resistivity. Indeed, in both MHD computation and in the T1 experiment it is observed that the fluctuations increase with edge resistivity [6]. In figure 6 the n-spectrum of the fluctuations is displayed for a case of high edge resistivity (solid curves) and lower resistivity (dashed curves). The experimental resistivity was changed by varying the edge electron temperature, which depends upon the plasma current. In the 3D, nonlinear, resistive MHD code the resistivity profile has the form $(1 - 9r\Upsilon)^2$; the width of the high resistivity edge region was varied through by selecting different values of the constant γ. In both the 3D, nonlinear, resistive MHD code (figure 6a) and experiment (figure 6b) the fluctuation energy roughly doubles as resistivity is increased (although the magnitude of the change in the experimental resistivity is uncertain). The reversal parameter F, a measure of the edge toroidal field strength, decreases with resistivity, as the enhanced fluctuation-induced current drive apparently is not fully able to compensate for the increased resistivity. The sensitivity of fluctuations to edge resistivity, and the change in resistivity with plasma current in T1 (presumably due to altered plasma-wall interactions), points to the need for care in the interpretation of deliberate experimental current scans.

4. Plasma rotation and mode locking

A specialized, high-speed Doppler spectrometer has been developed to measure the plasma rotation dynamics [7]. The spectrometer detects emission from C V impurity ions localized near the hot core of MST. Two opposing toroidal chordal views are simultaneously recorded for measurement of toroidal flow velocity. The system combines good resolution and throughput with high-speed parallel light collection.

Measurement precision of < 0.6 km/s has been demonstrated, with a digitization rate of 1 MHz and a corresponding analog bandwidth of 250 kHz.

The remarkably strong coupling between the plasma flow and the magnetic mode rotation is illustrated in figure 7, which displays the mode phase velocity measured with an edge magnetic coil array (figure 7a), the plasma rotation velocity measured with the Doppler spectrometer (figure 7b) and the magnetic field error at the vertical cut in the shell (figure 6c) [8]. A clear sequence is observed in which the sawtooth crash generates a sudden field error, for example at 12.5 ms, followed by a sudden deceleration of the mode velocity (or locking), followed by a sudden deceleration of the plasma flow. As the field error subsides, the sequence is reversed with the mode acceleration lagging behind the plasma acceleration.

The $m = 1$, $n = 6$ mode velocity is illustrated in figure 7; however, that mode is one of several large modes with $n \approx 5 - 8$ which are phase-locked to each other, forming a rotating, localized disturbance. For an initial interpretation of the mode locking dynamics, we qualitatively apply an MHD theory developed for tokamaks [9]. The theory treats a single mode, with a corresponding single magnetic island. The application of the theory to the RFP is only approximate since in the RFP several modes simultaneously interact with the field error, and the magnetic field pattern is likely stochastic, rather than a single island.

We are particularly interested in interpretation of the acceleration and deceleration timescales. In the mode locking theory the mode rotation velocity is determined by a competition between two forces acting on the plasma within the magnetic island : the decelerating electromagnetic force arising from the field error (a Lorentz force) and the accelerating viscous force arising from the rotating external bulk plasma. The electromagnetic braking force is large in the presence of the field error, and indeed the slowing down time from this force is of the order of the observed 100 μs slowing down time of the mode. We observe that the plasma slows down, also on a 100 μs timescale, but with about a 100 μs delay. If the observed plasma rotation corresponded to plasma external to a magnetic island, then one might expect that plasma to decelerate on a viscous timescale. However, classical viscosity yields a slowing down time of about 0.13 s, much longer than the observed timescale. A possible explanation, as described earlier, is that the separation between inner plasma (within an island) and outer plasma is invalid in the RFP, so that most of the plasma within the spectrometer view of C V ions (which extends roughly over the range $(0.3 < r/a < 0.6)$ experiences the electromagnetic torque.

The acceleration timescale of several ms is roughly equivalent to the particle confinement time in MST. A possible scenario is that (1) the sawtooth crash diminishes the radial electric field (concomitant with flattening of density and temperature profiles), (2) the radial field is then re-established by particle diffusion on a particle confinement timescale, (3) the bulk plasma accelerates through the growing E x B drift, and (4) the modes then accelerate by viscous momentum transfer from the bulk plasma to the plasma within the island (or stochastic) structure.

5. Conclusions

MHD theory explains a wide array of phenomena in the RFP. The cause of fluctuations is well-understood by MHD, with understanding now extending to details of nonlinear coupling. Recent observations of wave number spectra in T1 contain strong signatures of three-wave coupling. A key remaining question is whether magnetic fluctuations will diminish as the plasma temperature (and Lundquist number) increases.

In T1 and MST, measurements are consistent with the MHD theory of the dynamo. This is revealed in T1 by correlating changes in the current density profile with the appearance of specific modes. In MST, measurement of the MHD dynamo term ($\delta v \times \delta \mathbf{B}$) in the plasma edge can account for the edge plasma current in magnitude and time dependence through a sawtooth oscillation. Essentially, the mean-field Ohm's law is satisfied if the MHD dynamo term is included. The cause of the dynamo in the core of the plasma is not yet firmly established in experiment.

The RFP presents an opportunity for novel studies of mode locking physics. Measurement of plasma rotation reveals that the plasma and modes track each other remarkably well, with both decelerating in response to an impulsive field error with a slowing down time of 100 μs. Application of mode locking theory developed for a single mode interacting with a field error very roughly agrees with experiment. However, a mode locking theory is required which accounts for the presence of several modes locking (and interacting) simultaneously, as well as for the influence of field stochasticity on the process.

References

[1] Mazur S 1993 *Physica Scripta* **49** 233

[2] Nordlund P and Mazur S 1994 Plasma Phys. **1** 4032

[3] Ji H, Almagri A F, Prager S C and Sarff J S 1994 *Phys. Rev. Lett.* **73**, 668

[4] Ji H *et al* submitted to *Phys. Rev. Lett.*

[5] Ji H *et al*, 1992 *Phys. Rev. Lett.* **69** 616

[6] Nordlund P, Mazur S, Saetherblom H-E, Li G X, Brzozowski J H and Drake J R 1994 *Int'l Conf on Plasma Physics and Controlled Fusion Research.* IAEA-CN-60/A6/C-P-6

[7] Den Hartog D J and Fonck R J 1994 *Rev. Sci. Instrum.* **65** 3238

[8] Den Hartog D J, Almagri A F, Chapman, J T, Ji, H, Prager S C, Sarff J S, Fonck R J and Hegna C C 1995 *Phys. Plasmas* **2** 2281

[9] Fitzpatrick R and Hender T C 1991 *Phys. Fluids* **B3** 644

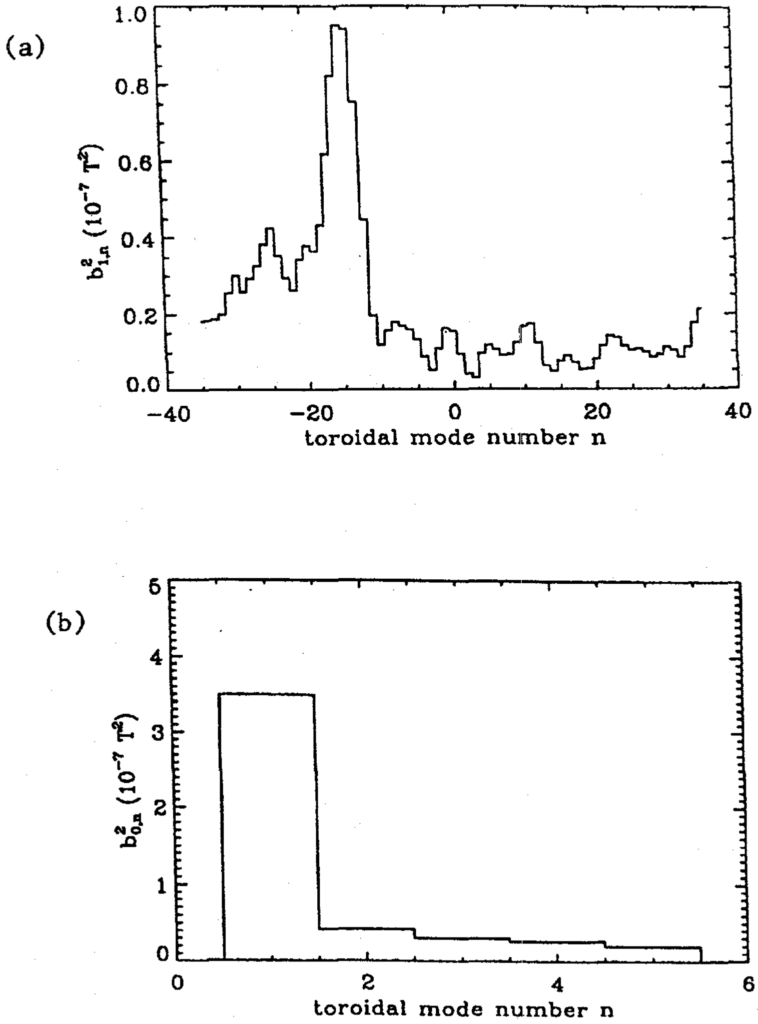

Figure 1. Toroidal mode number spectrum of (a) m = 1 magnetic oscillation and (b) m = 0 in Tl.

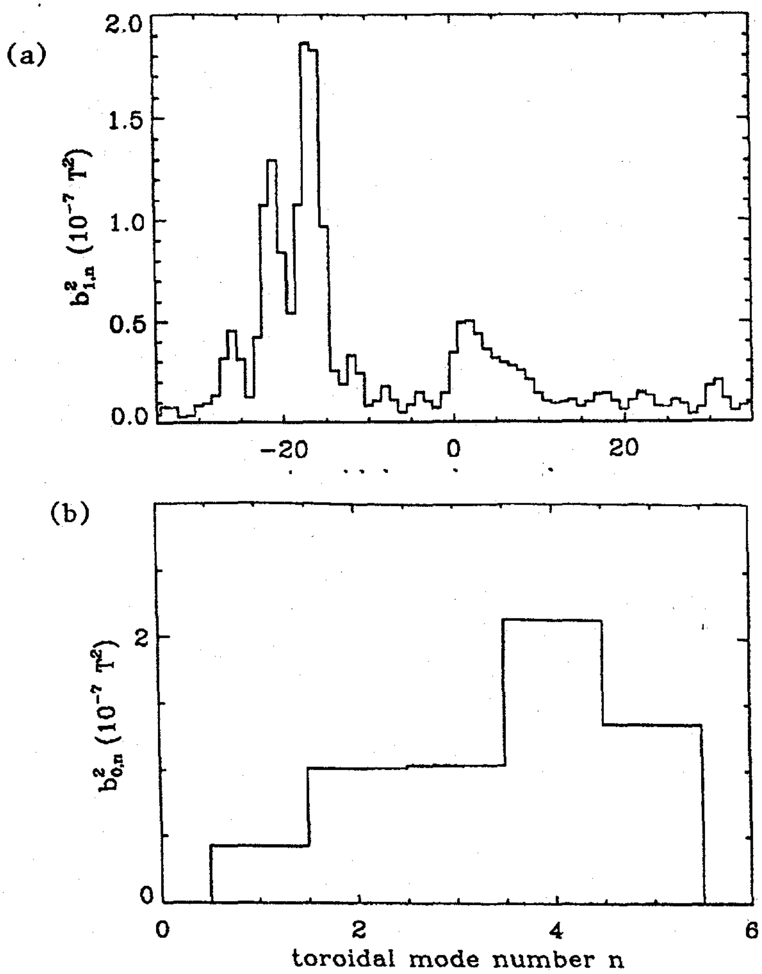

Figure 2. Toroidal mode number spectrum of (a) m = 1 magnetic oscillation and (b) m = 0 mode in T1 at particular time when n-spectrum of the m = 1 mode is double-peaked in T1.

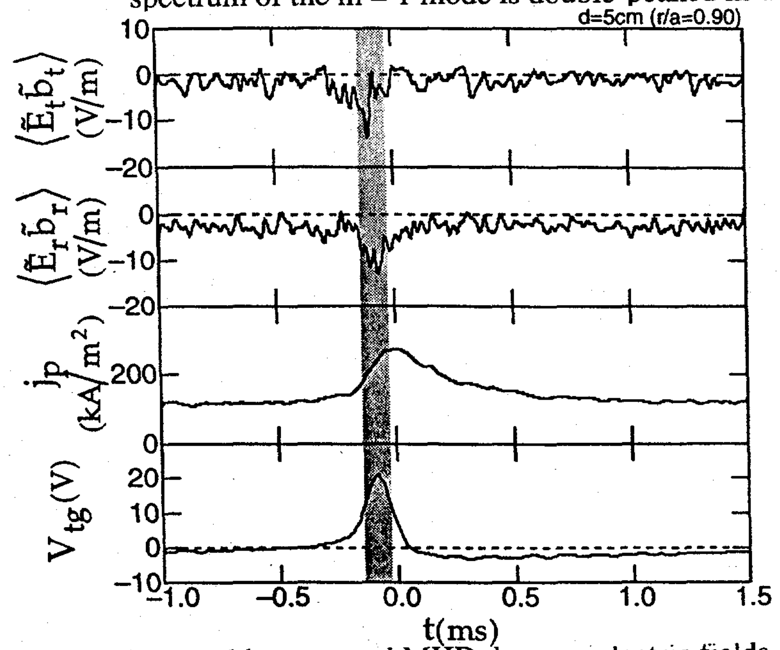

Figure 3. Ensemble-averaged MHD dynamo electric fields and local parallel current density during one sawtooth crash, measured at *r/a* = 0.90 in MST.

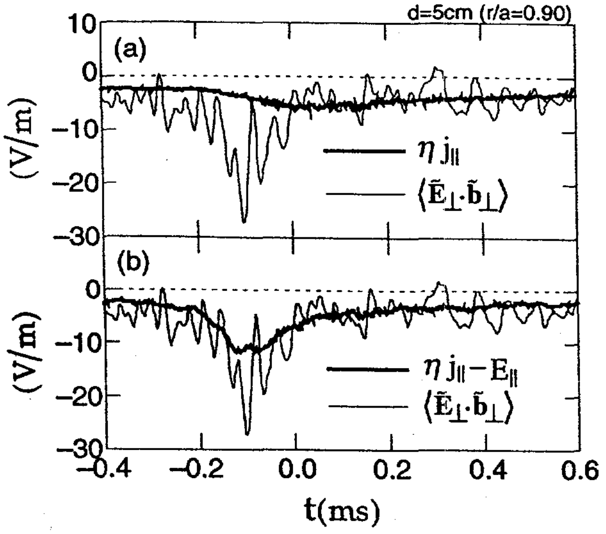

Figure 4. Comparison of MHD dynamo electric field $<\tilde{\mathbf{E}}_\perp \cdot \tilde{\mathbf{b}}_\perp>$ to (a) $\eta \mathbf{j}_{||}$ and (b) $\eta \mathbf{j}_{||} - \mathbf{E}_{||}$ during one sawtooth crash in MST. Rapid oscillations in $<\tilde{\mathbf{E}}_\perp \cdot \tilde{\mathbf{b}}_\perp>$ indicate experimental uncertainty.

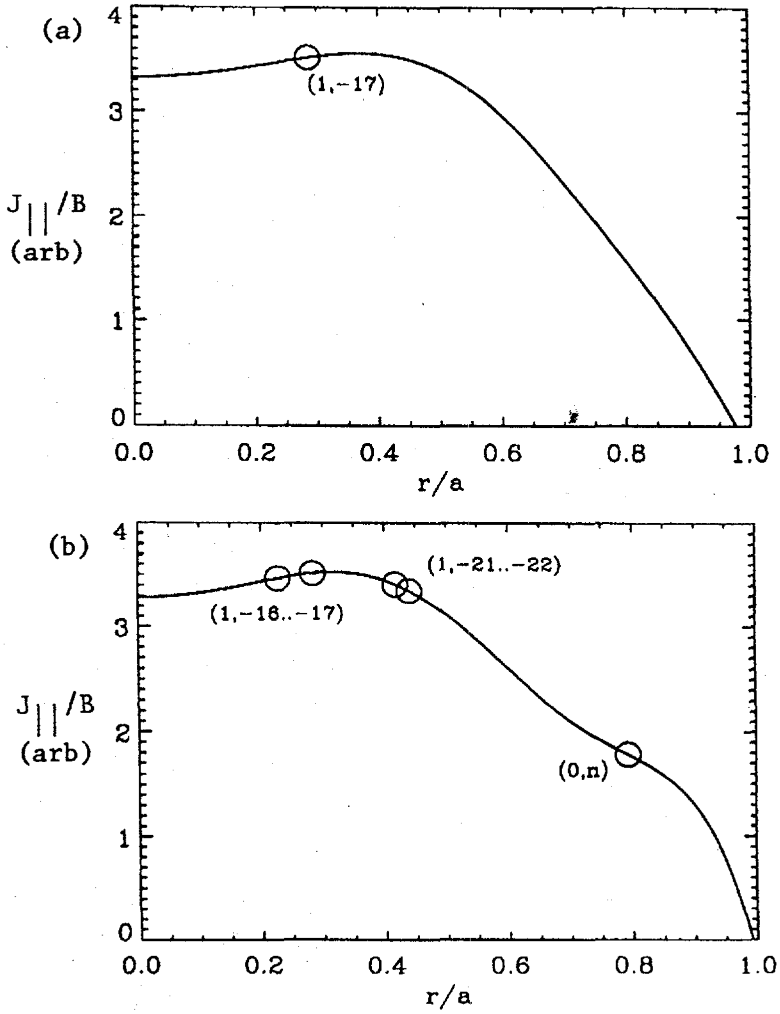

Figure 5. Radial profile of $\mathbf{J}_{||}/\mathbf{B}$ in T1 (a) at a time when the m = 1, n = -17 mode dominates and (b) for the usual case with several dominant modes. The locations of specific mode-resonant surfaces.

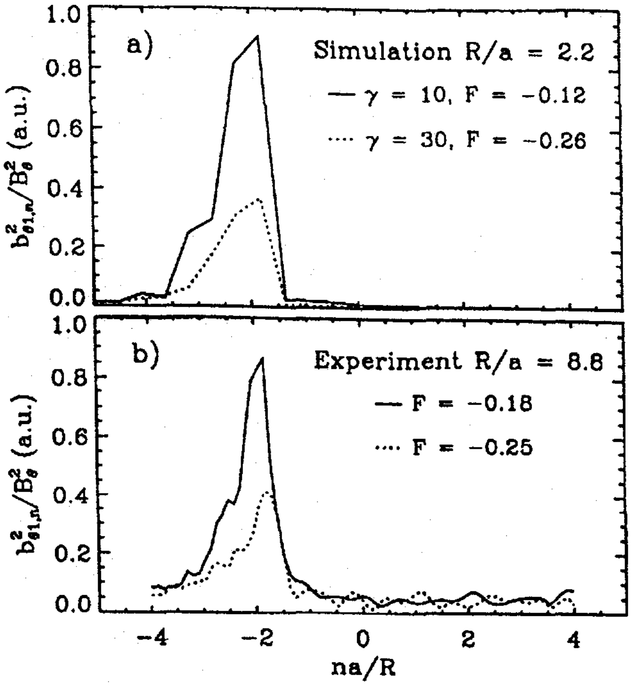

Figure 6. Toroidal mode number spectrum of magnetic fluctuations (a) as predicted by MHD computation, and (b) as measured in the T1 experiment. The dotted curve corresponds to a relatively broad high resistivity edge region, the solid curve to a narrower resistive edge.

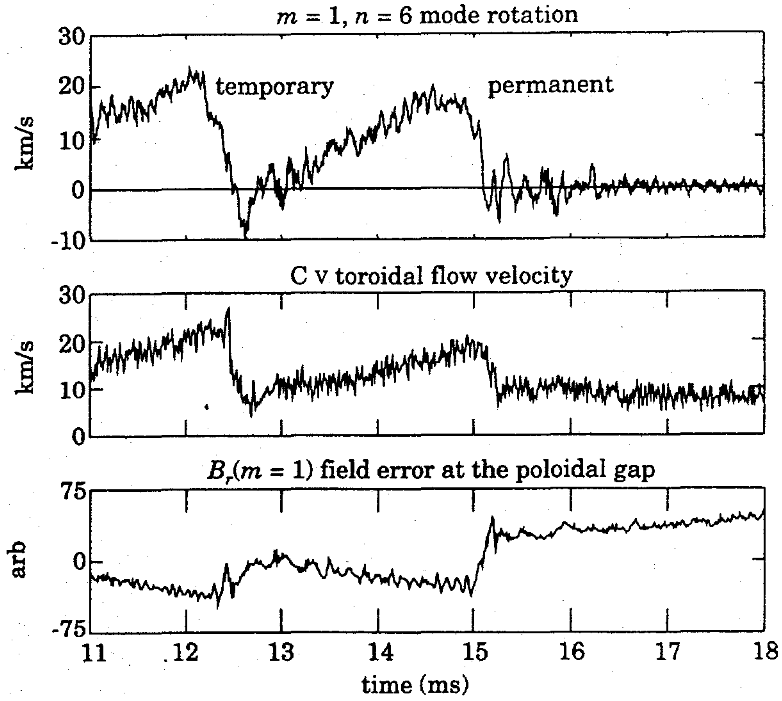

Figure 7. (a) Toroidal phase velocity of m = 1, n = 6 magnetic oscillation, measured with magnetic coils, (b) toroidal flow velocity of carbon V ions, measured with Doppler spectroscopy, and (c) radial magnetic field error (m=1) component at the vertical cut in the conducting shell in MST.

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