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Dynamo and anomalous transport in the reversed field pinch

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Abstract. The reversed field pinch (RFP) is an effective tool in the study of the macroscopic consequences of magnetic fluctuations, such as the dynamo effect and anomalous transport. Several explanations exist for the dynamo (the self-generation of plasma current)—the magnetohydrodynamic dynamo, the kinetic dynamo and the diamagnetic dynamo. There is some experimental evidence for each, particularly from measurements of ion velocity and electron pressure fluctuations. Magnetic fluctuations are known to produce energy and particle flux in the RFP core. Current profile control is able to decrease fluctuation-induced transport by a factor of five. Improved confinement regimes are also obtained at deep reversal and, possibly, with flow shear.

1. Introduction

The reversed field pinch (RFP) is a toroidal fusion concept which can be viewed simplistically as a tokamak with the toroidal magnetic field reduced about a factor of ten (for a given plasma current). This weak magnetic field yields a set of attractive features for a fusion power source: normal (not superconducting) coils, high beta, weak field and force at coils, high power density, simplified maintenance, absence of disruptions (empirically), and possibly free choice of aspect ratio [1]. However, the weak field also yields a safety factor which is less than unity everywhere in the plasma. This is unfavourable for resistive magnetohydrodynamic (MHD) stability, and results in fluctuations in the magnetic field which are large—about 1% of the equilibrium field. These fluctuations control much of the macroscopic dynamics of the plasma. It is believed that the spatial distribution of the plasma current (i.e. spontaneous current generation) and plasma transport are controlled largely by the fluctuations. Thus, in addition to its potential fusion attractiveness, the RFP is a wonderful vehicle for the study of magnetic fluctuations. This paper briefly reviews the powerful influence of magnetic fluctuations on the macroscopic plasma behaviour—the dynamo effect and anomalous transport—as well as methods to control these effects.

RFP research has a long history, beginning with the discovery of field reversal in the ZETA device in the 1960s [2]. The intriguing, favourable stability properties that accompanied reversal stimulated research in the 1970s. Experiments then were characterized by short-pulse (hundreds of microseconds), dense plasmas with confinement times in the 100 μs range [3]. The 1980s were marked by a group of very productive experiments, with confinement times up to 0.5 ms, minor radii of about 0.2 m and plasmas that were sufficiently long-lived (tens of milliseconds) to accommodate detailed studies of RFP equilibrium and fluctuations [4–7]. During this decade the nonlinear MHD foundation of the RFP began construction [8, 9], following on from the insight that the RFP can be described as a minimum-energy, magnetically-relaxed state [10]. The work in these experiments laid the basis for the

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experiments of the 1990s which increased the plasma size twofold (to minor radii of 0.5 m) and the confinement time tenfold (to 5 ms). Most importantly, recent physics results, reviewed in this paper, have led to new insights and a re-appraisal of the RFP.

The world RFP program consists of four major experiments and a number of smaller experiments. The four major experiments are RFX in Italy [11], TPE-RX in Japan [12], MST in the US [13], and Extrap-T2 [14] in Sweden, with the parameters described in table 1. Three devices—RFX, TPE-RX and MST—contain plasmas of similar size (minor radii of about 0.5 m). Each plasma is considered large in the RFP context, being about twice the minor radius of the RFP plasma experiments which existed throughout the 1980s. The three devices have different toroidal volt-second capability, which provides different plasma current and pulse length capabilities. RFX has a design current of 2 MA (with currently obtained values of about 1 MA), TPE-RX, which began operation in December 1997, has a design current of 1 MA and MST operates at 0.5 MA. T2 is a refurbishment of the resistive shell OHTE experiment which operated at General Atomics in the 1980s. The four experimental programs operate in close coordination with complementary goals. They build upon experimental results obtained in earlier decades, particularly at the Culham Laboratory, the Los Alamos National Laboratory, General Atomics and the Tokyo University.

Table 1. The largest devices in the world RFP program.

Device	Minor radius, a (m)	Major radius, R (m)	Current, I (MA)	Pulse length (s)
RFX	0.46	2.0	1 (2 design)	≈ 0.1 ($\sim$0.3 design)
TPE-RX	0.45	1.72	1	≈ 0.08
MST	0.51	1.50	0.5	≈ 0.08
Extrap-T2	0.18	1.24	0.3	≈ 0.01

A conceptual basis for understanding the equilibrium magnetic field profiles of the RFP is offered by the conjecture by Taylor [15] that a pressureless plasma relaxes to a state in which the magnetic energy is minimized subject to the constraint that magnetic helicity is conserved (magnetic helicity $= \int \boldsymbol{A} \cdot \boldsymbol{B}\, \mathrm{d}V$, where $\boldsymbol{A}$ and $\boldsymbol{B}$ are the magnetic vector potential and magnetic field, and the integral extends over the plasma volume). Magnetic helicity is a topological measure of the knottedness of the magnetic field lines, and it is an invariant for an ideal plasma. The above minimization yields the simple condition $\nabla \times \boldsymbol{B} = \lambda \boldsymbol{B}$, where λ is a spatial constant (i.e. $j/B =$ constant). The solution of this equation for a cylindrically and axially symmetric plasma yields the result that the axial (or toroidal) field $B_z = J_0(\lambda r)$, the zero-order Bessel function. The remarkable feature of this solution is that it qualitatively resembles RFP experiments—the function decreases monotonically with radius and reverses sign near the plasma boundary. The Taylor state does not match the experimental state in detail; experiments are only partially relaxed in that j/B tends to be constant over the inner half of the plasma, but then decreases to zero at the wall. Nonetheless it approximates much of the equilibrium and serves as an invaluable framework for the interpretation of RFP behaviour, suggesting that the RFP has a 'natural' current density profile. Often in experiments, plasma relaxation occurs cyclically. A sawtooth oscillation is evident, in which the crash phase represents a sudden relaxation event. From global magnetic measurements combined with equilibrium modelling, the magnetic energy and helicity have been inferred in experiments [16], revealing that the magnetic energy is indeed decreased (by about 8%), while the helicity changes relatively little (about 3%), as shown in figure 1.

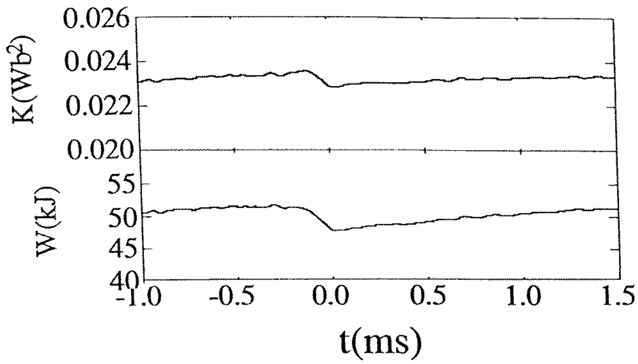


Figure 1. Magnetic helicity and magnetic energy as a function of time throughout a magnetic relaxation event, as inferred from equilibrium modelling of MST.

Thus, the Taylor conjecture appears to carry qualitative, if not quantitative, significance for the RFP. However, the focus of the present paper is on the dynamics which underlie plasma relaxation and transport, with particular attention to the experimental status of our understanding. For both the dynamo and anomalous transport we describe experimental tests of the standard nonlinear MHD model, as well as discoveries which lie outside that model. The dynamo process of spontaneous current generation in the plasma, which drives the plasma towards a Taylor state, is discussed in section 2. Magnetic fluctuations which lead to the dynamo, also lead to anomalous transport of particles, parallel momentum and energy. Our understanding of these processes is discussed in section 3. The understanding of dynamo and transport has led recently to a new thrust in RFP research—the control of fluctuations and transport. Initial experiments demonstrate substantial reduction of transport, as discussed in section 4. Section 5 closes with a summary and discussion.

2. The dynamo effect

A striking feature of the RFP is that the plasma current parallel to the magnetic field is only partially attributed to the applied toroidal electric field [17]. This is easily evident at the radius where the toroidal magnetic field vanishes. At this location the parallel (poloidal) current is non-zero, as is required by Ampère's law to sustain the gradient and reversal of the toroidal field. Yet, the parallel electric field is zero. Hence, an additional effect must drive the plasma current.

In MHD, this effect is the fluctuation-induced electromotive force which appears in the parallel component of the mean-field Ohm's law

$$\langle \boldsymbol{E} \rangle + \langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle = \eta \langle \boldsymbol{j} \rangle \tag{1}$$

where $\langle\ \rangle$ indicates a magnetic surface average (the 'mean' fields), and $\delta \boldsymbol{v}$ and $\delta \boldsymbol{B}$ are velocity and magnetic field fluctuations, respectively. The fluctuation-induced term, $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle$, is referred to as the dynamo effect and is the term which is conjectured to drive spontaneous magnetic field generation in the Earth and many astrophysical bodies [18]. Of course, the cause of the fluctuations varies in different laboratory and natural settings. In the RFP, the fluctuations are generated by tearing instabilities.

The dynamo problem for the RFP has been treated extensively through MHD [19–23], particularly computational solution of the full nonlinear, resistive, MHD equations. To date, these equations have been investigated extensively in cylindrical geometry [24]. Toroidal effects are expected to be modest since the toroidal magnetic field is weak. The strong dynamo effect is manifest through the computational evaluation of each term in the mean-field Ohm's law, displayed in figure 2. The parallel component of the applied axial electric field decreases with radius as a result of the strong shear in the magnetic field. It is seen (figure 2(a)) that not only is there a non-zero current at the radius where the electric field is zero, but across the entire plasma the current cannot be accounted for by the electric field. The edge requires an extra current drive mechanism, whereas the centre requires spontaneous current drive counter to the electric field driven current. The computed $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle$ dynamo, shown in figure 2(b), provides the additional current drive, and balances Ohm's law.

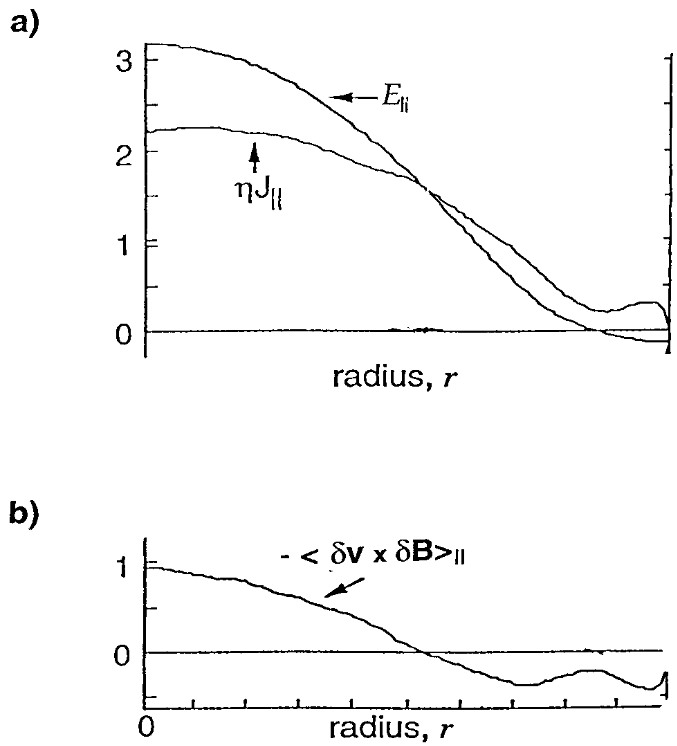


Figure 2. The radial profile of each term in the parallel mean-field Ohm's law, equation (1), showing (a) the mean electric field and current density terms and (b) the fluctuation-induced dynamo term, computed from nonlinear, resistive MHD equations.

A clear test of the MHD dynamo theory is to measure each term in Ohm's law, equation (1), a task which has been underway in recent years. The task is aided by the cyclic nature of the dynamo. For example, the toroidal magnetic flux in the plasma is increased suddenly, during sawtooth crashes which represent sudden dynamo events, as illustrated in figure 3. In the edge of the MST plasma the dynamo term $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle$ has been measured by inferring the fluctuating velocity from the measured fluctuating $E \times B$ drift which arises from the fluctuating electric field [25]. The other two terms in Ohm's law were estimated from experimental data, with the result that the mean-field Ohm's law, equation (1), was satisfied both during a sawtooth crash (a dynamo event) and between crashes.

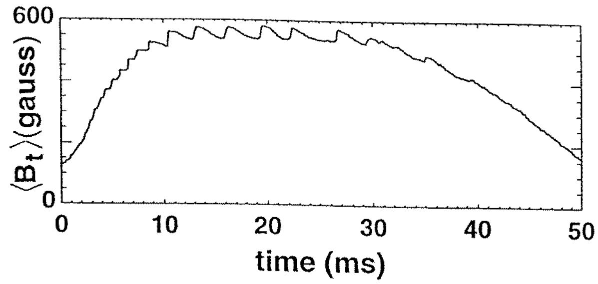


Figure 3. The toroidal magnetic flux within the plasma volume against time (taken from MST).

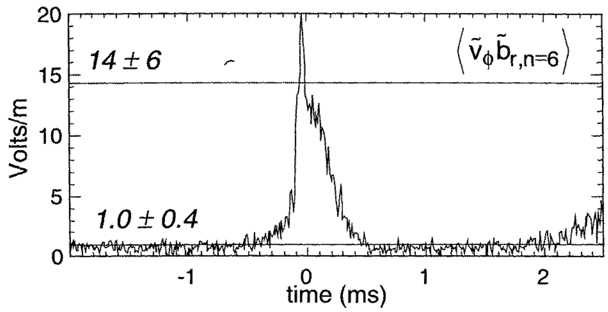


Figure 4. One component of the MHD dynamo ($\langle \delta v_\phi \delta B_r \rangle$), contributed from the toroidal mode number $n = 6$, as a function of time through a sawtooth cycle. Velocity fluctuations were measured by Doppler spectroscopy in the MST core and magnetic fluctuations by an edge coil array.

Direct measurement of the fluctuating flow velocity has been obtained recently by fast Doppler spectroscopy [26]. Doppler emission from carbon ions has been detected with 10 μs time resolution. The measured fluctuating flow has been correlated with magnetic fluctuations to form the dynamo term $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle$, one component of which is shown in figure 4. During a sawtooth crash the dynamo electromotive force becomes extremely large ($\sim$15 V m^{-1}) to balance the strong inductive electric field which accompanies the current profile relaxation. The view of the dynamics is that the tearing modes grow as the current profile steepens during the slow phase of the sawtooth oscillation. At sufficient tearing mode amplitude, the fluctuation-induced dynamo effect causes the current profile to flatten. This generates an inductive electric field (back electromotive force (EMF)) in a direction to peak the profile. To permit the plasma to reach its relaxed state the dynamo effect grows yet larger, maintaining the Ohm's law balance. The above dynamics in MST are consistent with the standard MHD model (although the full vector dynamo term has not yet been measured).

Langmuir probe measurements of the dynamo were also conducted in the edge of the TPE-1RM20 experiment, with a surprising result [27]. The MHD dynamo generated by the fluctuating $E \times B$ drift was measured to be small. However, a pressure-driven dynamo term in Ohm's law was measured to account roughly for the self-generated current. This can be understood by including the electron pressure term in the generalized, parallel mean-field Ohm's law,

$$\langle \boldsymbol{E} \rangle_\parallel - \eta \langle \boldsymbol{j} \rangle_\parallel = -\langle \delta E_\perp \delta B_\perp \rangle - \frac{\langle (\delta p_\perp) \delta B_\perp \rangle}{ne}.$$

The first term on the right-hand side is the standard dynamo effect obtained from the $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle$ term including only the contribution to $\delta \boldsymbol{v}$ from the $\delta E \times B$ drift. The second term represents the contribution to the $\langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle$ term from the fluctuating electron diamagnetic drift which arises from a fluctuating electron pressure. If the pressure fluctuation correlates with the magnetic field fluctuation, a 'diamagnetic' dynamo effect results. The edge conditions in TPE-1RM20 are somewhat different than in MST (for example, TPE-1RM20 is more collisional), but the cause for the different results is not yet known.

A second dynamo effect outside the standard MHD model is the adjustment of the current density profile by the transport of electron parallel momentum (or current) in the radial direction by magnetic fluctuations. This transport process, known as the 'kinetic dynamo' [28], is discussed further in section 3. In many experiments fast electrons exist at the plasma edge with parallel energies characteristic of the central temperature [29]. This implies that perhaps the electrons originate from the plasma centre and are rapidly transported to the plasma edge. However, definitive measurement of the kinetic dynamo requires measurement of new fluctuating quantities, as discussed in section 3. In addition, the inclusion of the self-consistency constraint of Ampère's law may inhibit the kinetic dynamo mechanism [30].

Although the theoretical basis for the MHD dynamo is compelling, and some experimental tests are supportive, it remains to be determined which of the few possible dynamo mechanisms dominates the variety of plasma conditions found in the various RFP experiments. We conjecture that, although the relative influence of various dynamo mechanisms may be situation dependent, the mechanisms will always sum to yield the natural current density profile of the partially relaxed Taylor-like state. The MHD velocity and magnetic field fluctuations can adjust, in the presence of other dynamo contributors, to maintain the relaxed profile.

3. Anomalous transport

It has long been recognized that radial magnetic field fluctuations can cause magnetic field lines to depart from concentric surfaces and wander chaotically throughout the plasma volume. The break-up of magnetic surfaces results from fluctuations which are resonant with the equilibrium magnetic field; i.e. the component of the wavevector parallel to a field line vanishes ($\boldsymbol{k} \cdot \boldsymbol{B} = 0$) at some radius. When this condition is satisfied the fluctuation amplitude is constant on an equilibrium field line, causing the actual field line to deviate significantly from its trajectory in the absence of the fluctuations. Nonlinear MHD computation predicts that multiple unstable resonant instabilities in the RFP yield magnetic stochasticity throughout much of the plasma volume, except perhaps the edge.

The stochastic nature of the field is difficult to measure in experiments. To detect a stochastic field line trajectory would require simultaneous measurement of the magnetic field at a large number of locations (of the order of 1000) in the plasma simultaneously. However, the transport arising specifically from particle motion along a stochastic magnetic field is measurable. For example, the energy flux in the radial direction, arising from particle motion along the field, is given by

$$Q_r = \langle \boldsymbol{Q}_\parallel \cdot \boldsymbol{e}_r \rangle = \langle Q_\parallel \boldsymbol{b} \cdot \boldsymbol{e}_r \rangle$$

where $Q_\parallel$ is the energy flux parallel to the magnetic field, and $\boldsymbol{e}_r$ and $\boldsymbol{b}$ are unit vectors in the radial and magnetic field directions, respectively. The contribution to the mean (magnetic-surface-averaged) energy flux arising from fluctuations is given by

$$Q_r = \frac{\langle \delta Q_\parallel \delta B_r \rangle}{\langle B \rangle}$$

where $\delta Q_\parallel$ is the fluctuation in the parallel energy flux. Hence, the radial electron energy flux specifically driven by magnetic fluctuations can be determined in experiments by measuring the parallel component of the fluctuating electron energy flux and correlating it with the fluctuating magnetic field.

Similarly, the radial flux of particles and momentum, driven by magnetic fluctuations, is given by

$$\text{particle flux} = \frac{\langle \delta j_\parallel \delta B_r \rangle}{e\langle B \rangle}$$

$$\text{momentum flux} = \frac{\langle \delta p_\parallel \delta B_r \rangle}{\langle B \rangle}$$

where $\delta j_\parallel$ and $\delta p_\parallel$ are the fluctuating, parallel current density and pressure for a given species. The momentum flux constitutes the kinetic dynamo mechanism discussed in section 2. It has not yet been measured; definitive test of the kinetic dynamo awaits such a measurement. However, the energy and particle fluxes from magnetic fluctuations have been measured in the outer 20% of the plasma radius [31, 32]. These fluxes are shown to account approximately for the transport inside the plasma (within the reversal surface at about 85% of the wall radius), but not in the extreme edge. This data, shown in figure 5 for the energy flux, is consistent with the expectation that the field in the plasma interior is stochastic, whereas the field in the extreme edge may be well ordered.

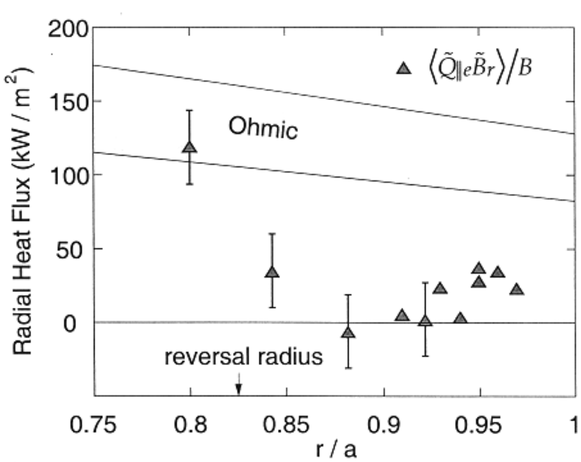


Figure 5. The radial electron energy flux driven by magnetic fluctuations against radius. The shaded region is the estimated total energy flux.

An intriguing feature of the magnetic fluctuation-induced electron energy transport is that it is much smaller than the Rechester–Rosenbluth expression [33] for test particle transport in a stochastic field. The magnitude of the electron thermal conductivity, χ_e, at $r/a \sim 0.8$ is of the order of the Rechester–Rosenbluth expression, but with a velocity characteristic of the ions; i.e.

$$\chi_e \sim v_{ti} \left(\frac{\delta B}{\langle B \rangle} \right)^2 L_c$$

where v_{ti} is the ion thermal speed and L_c is a parallel correlation length (measured to be of the order of the minor radius). This estimate of the magnitude of χ_e suggests that ambipolarity may play a role in heat transport. A possible theoretical explanation for such an effect was developed by considering the constraint on the magnetic fluctuations by Ampère's law and quasineutrality [34].

4. Control of magnetic fluctuations and transport

A major objective of the RFP research program worldwide is to reduce magnetic fluctuations and transport. This goal is imperative for the fusion application of the RFP, but control of magnetic fluctuations would also offer new insight into the relationship between fluctuations and transport. Since the magnetic fluctuations are understood to arise from resistive MHD instabilities, it is expected that the fluctuation amplitude will depend on the electrical resistivity, expressed through the dimensionless Lundquist number, $S = \tau_r/\tau_a$, where τ_a is the Alfvèn transit time and τ_r is the resistive diffusion time. If we assume that the transport scales as the Rechester–Rosenbluth expression and that the fluctuations scale as an inverse power of S, $\delta B/B \sim S^{-\alpha}$, we find that the confinement is a strong function of the scaling exponent α. For example, if $\alpha = 1/2$, then the energy confinement time will scale as

$$\tau_e \sim \frac{a^2 j^{3/2}}{n^{3/2}}$$

where j and n are the plasma current density and density. This strong increase of confinement with plasma current proves extremely favourable for projection to an RFP fusion source. It can alternatively be derived from two assumptions—constant beta and classical resistivity. This scaling describes the experimental database [35], considering only the best discharges (usually at relatively low plasma current) from each device. Scaling within a given device is less clear, as discussed below.

On the other hand, if $\alpha = 0$ (fluctuations independent of Lundquist number), then

$$\tau_e \sim \frac{a^2 j^{3/2}}{n^{3/2}} \frac{\beta^{3/2}}{aT^2}.$$

The strong inverse temperature dependence in this case proves highly unfavourable for an RFP reactor. Hence, scaling of RFP confinement depends sensitively on the dependence of magnetic fluctuations on Lundquist number (if the transport scales as the Rechester–Rosenbluth expression).

There have been a variety of theoretical [36–39] and computational studies of the S scaling of magnetic fluctuations, with results varying from $\alpha = 0$ to $\alpha = 1/2$. Nonlinear MHD computational results yield $\alpha \sim 0.2$ [40, 41]. There have been limited experimental tests of S scaling, with α lying between 0.1 and 0.4 [42–44]. The S scaling of fluctuations and confinement remains a critical issue. Key information will be contributed by the RFX and TPE-RX experiments, which have plasma current capabilities of 2 MA and 1 MA, respectively. These experiments will reveal whether fluctuations and transport are naturally 'controlled' by favourable scaling. Of course, it is possible that S may not be the most important dimensionless parameter; the viscosity may prove important, as may other parameters if non-MHD effects become important for reconnection in the RFP at high temperature.

An additional approach to reduce fluctuation-induced transport in the RFP is to control the current density profile—the energy source for the fluctuations. The radial profile of the current density parallel to the magnetic field is usually peaked in the plasma centre. MHD theory predicts that if the profile is flattened, brought closer to the Taylor state, then fluctuations will be decreased [45, 46]. This effect was examined through nonlinear, resistive MHD computation. The usual MHD equations were supplemented by an additional term which represents a parallel force on the electrons, representative of an auxiliary current drive mechanism. The computation

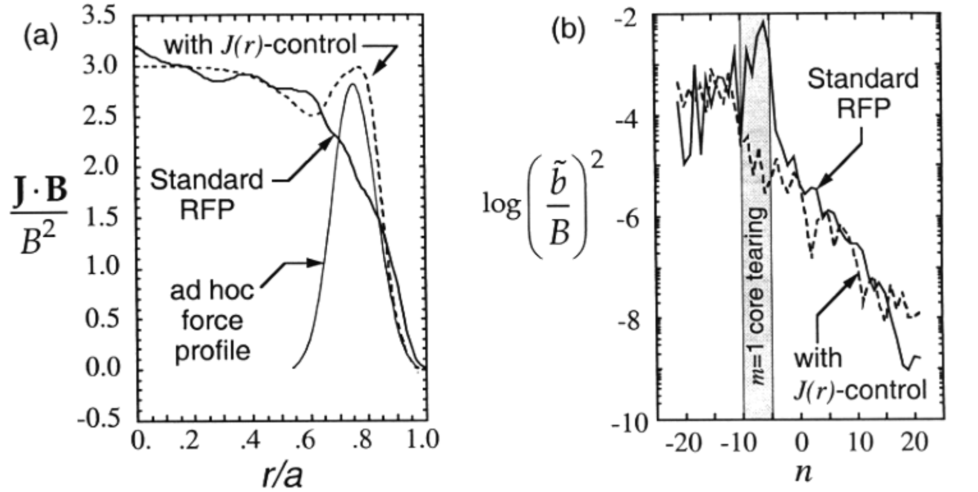


Figure 6. Prediction of nonlinear, resistive MHD computations for (a) the current density profile against radius in the outer region and (b) the toroidal mode number spectrum of magnetic fluctuations, both with and without auxiliary current drive in the outer region.

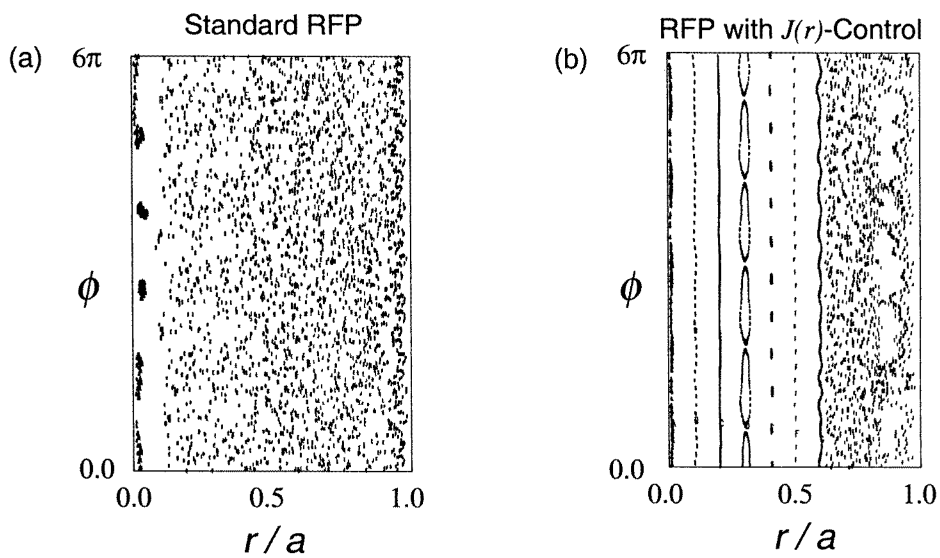


Figure 7. MHD prediction for the magnetic field line puncture plot in the radial–toroidal plane (a) without auxiliary current drive and (b) with auxiliary current drive.

yields the self-consistent current density profile (including the alteration of the dynamo effect by the *ad hoc* auxiliary current). The addition of the auxiliary current in the outer region of the plasma (figure 6(a)), leads to a drastic reduction in the dominant core-resonant tearing modes (figure 6(b)), which in turn causes magnetic stochasticity to be decreased and concentric magnetic surfaces to form in the plasma core (figure 7).

The first experimental realization of RFP current profile control has been to apply suddenly an inductive poloidal electric field during a discharge [47]. Since the magnetic field in the plasma outer region is dominantly poloidal, the pulsed electric field produces a parallel current in the edge. The inductive technique (called pulsed poloidal current drive, (PPCD)) is inherently transient. Nonetheless, application of this technique in MST has succeeded in halving the magnetic fluctuation amplitude. The effect on the plasma is to decrease the ohmic input to the plasma threefold, increase beta by nearly 50% and increase the energy confinement time by about a factor of five, as shown in table 2. The effect of PPCD on magnetic fluctuations and ohmic input power is depicted in figure 8. The correlation in time between the magnetic fluctuations and input power, seen in figure 8 even for standard discharges, suggests a strong causality between the two quantities.

Table 2. Plasma parameters with and without pulsed poloidal current drive (PPCD) in MST.

	Standard Discharge	With PPCD
Magnetic fluctuations	1.3%	0.7%
Electron temperature	400 eV	600 eV
Ohmic input power	$\sim$ 4.5 MW	$\sim$ 1.5 MW
Energy confinement time	$\sim$ 1.3 ms	$\sim$ 6 ms

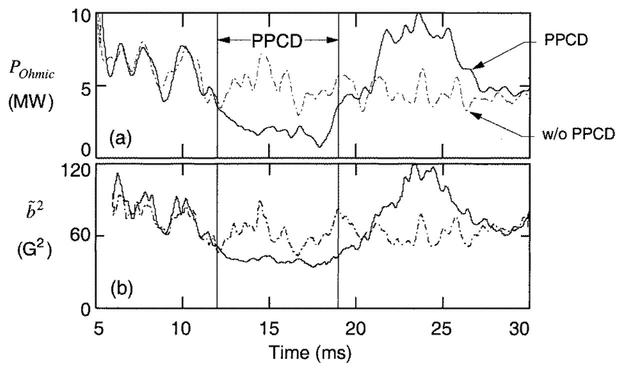


Figure 8. Magnetic fluctuations and ohmic input power against time, with and without pulsed poloidal current drive (PPCD) in MST.

Recent studies in RFX reveal that the core thermal conductivity decreases substantially during PPCD [48]. In standard RFP plasmas, the electron temperature profile is relatively flat over the inner half of the RFP plasma, indicative of the high transport that is expected to result from magnetic stochasticity. During PPCD, the electron temperature becomes centrally peaked, likely providing the first RFP plasmas in which substantial temperature gradient is maintained in the core. The ultimate lower limit to fluctuations and transport achievable with current profile control is not yet known and awaits the implementation of finer methods of profile control.

Confinement improvement by current profile control rests on a firm theoretical foundation. In recent years, a variety of enhanced confinement regimes have been discovered in RFP experiments. Neither their cause nor their potential is yet understood, but they constitute intriguing new endeavours. The influence of flow shear on turbulence has been an enduring and intensively studied topic for the tokamak and other magnetic configurations. Flow shear also exists in the RFP, with some initial evidence for a favourable influence on confinement. In RFX, the $E \times B$ flow has been measured in the plasma edge and reveals a double shear

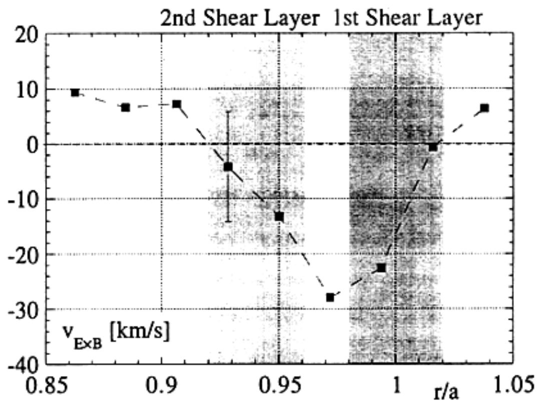


Figure 9. $E \times B$ flow velocity against radius in the edge of RFX.

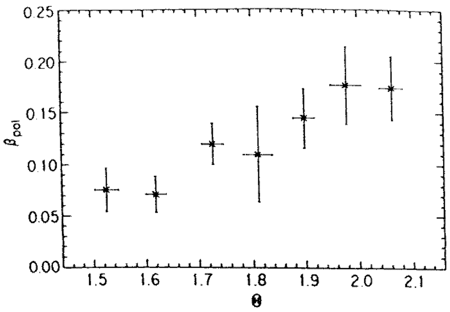
layer, with the electric field direction reversing [49, 50], as shown in figure 9. The $E \times B$ flow is consistent with the edge flow measured spectroscopically. Electrostatic fluctuations, and the particle transport induced by them (measured with Langmuir probes), decreases within the innermost shear layer. Active control of the flow shear has been implemented with biased electrodes inserted into the plasma edge. In MST, the particle confinement time improves by about 50% with probe biasing [51]. The energy confinement time is unaffected, consistent with the observation on many RFP experiments that electrostatic fluctuations determine edge particle transport, but not edge energy transport.

Improved confinement has also been observed if the plasma is maintained at deep reversal (reversal surface relatively far from the boundary), under particularly clean wall conditions. In deeply reversed discharges in the TPE-1RM20 device, magnetic fluctuations decrease about threefold, while the stored energy, plasma beta and energy confinement time all double [52]. The changes in magnetic fluctuations and beta are indicated in figure 10.

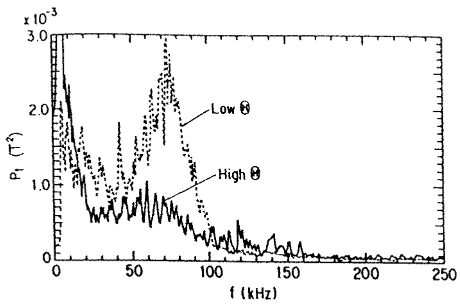
Possibly related phenomena occur in MST, in which discharges at deep reversal also show energy confinement improvement (threefold) as both magnetic and electrostatic fluctuations decrease [53]. The decrease in magnetic fluctuations suggests that perhaps the confinement improvement in both devices arises from changes in the equilibrium magnetic field, such as an increase in magnetic shear. However, it is also observed in MST that a narrow $E \times B$ shear layer develops in the edge, in the vicinity of particularly reduced electrostatic fluctuations. The collection of results on these recent, improved confinement regimes is not yet well understood. The relative contributions of flow shear, current profile effects, electrostatic fluctuations and magnetic fluctuations are yet to be determined.

5. Summary and discussion

The RFP is an effective vehicle for the study of the macroscopic consequences of magnetic fluctuations, such as the dynamo effect and anomalous transport. The existence of a dynamo effect—the self-generation of plasma current and magnetic field—is clear. A large plasma current flows (several hundred kiloamps in high current RFP plasmas) which is not accountable by the applied electric field. A well developed nonlinear MHD theory can explain the current as arising from an electromotive force ($\langle v \times B \rangle$) from tearing fluctuations. The dynamo electromotive force is similar to that conjectured to explain natural dynamos, although the



(a)



(b)

Figure 10. (a) Poloidal beta and (b) magnetic fluctuation power as a function of theta in TPE-1RM20. The parameter theta, the ratio of the poloidal magnetic field at the wall to the volume-averaged toroidal magnetic field, increases with the depth of field reversal.

cause of the fluctuations can be different. Measurement of the MHD dynamo effect with Langmuir probes in the plasma edge agrees with theory, showing that the mean-field Ohm's law is satisfied with the $\langle v \times B \rangle$ term included. Core dynamo measurements, in which flow velocity fluctuations are measured spectroscopically, also demonstrate a large contribution to current flow from the $\langle v \times B \rangle$ dynamo, although quantitative measure of each term in Ohm's law is not yet possible in the core. This dynamo effect may also occur in other laboratory circumstances, such as the spheromak and tokamak sawtooth oscillations.

The confirmation and generality of the MHD description of the dynamo in the RFP is not yet established, despite a convincing theory and some significant features of experimental agreement. Two possible dynamo effects beyond the standard MHD model have been investigated. First, under some experimental conditions a pressure-driven dynamo occurs which depends on the product of the fluctuating electron pressure and the fluctuating magnetic field. This effect can be viewed as arising from a $\langle v \times B \rangle$ term in which v is the fluctuating electron diamagnetic drift. Second, the 'kinetic dynamo' is a transport effect in which parallel current is transported radially by a stochastic magnetic field. The occurrence of fast electrons in the RFP edge may be consistent with this mechanism, although direct measure of the transport process awaits. We conjecture that, although the relative influence of various dynamo mechanisms may be situation dependent, the mechanisms will always sum to yield the natural current density profile of the partially relaxed Taylor-like state.

Magnetic fluctuations are well appreciated as drivers of the radial transport of particles and energy. Recent measurement of radial energy and particle flux from magnetic fluctuations demonstrates the importance of this effect. Hence, the scaling of magnetic fluctuations and transport with appropriate plasma parameters, such as the Lundquist number, is a key issue. High-current RFP experiments presently underway will provide critical physics scaling information. New techniques to control fluctuation-induced transport are also being developed, with extremely encouraging recent results. Reduction of the energy source for the fluctuations, via current density profile control, succeeds in dramatically reducing fluctuations and increasing confinement, particularly in the core. In addition, improved confinement regimes have been developed empirically, but are not yet understood. Flow shear is observed in the RFP; its relation to improved confinement represents a new theme for the RFP.

The above results have relevance for the fusion application of the RFP. The RFP, and other $q < 1$ magnetic configurations, have long been considered flawed as fusion reactors since the relatively large magnetic fluctuations drive anomalous transport. The recent results on a variety of experiments suggest that there may be methods to eliminate magnetic fluctuation-induced transport as a condemnatory feature. Initial results on reducing such transport are very encouraging. Hence, it is timely to improve confinement further, such as through the implementation of methods for the fine control of the current profile, and to investigate other key RFP physics issues. In particular, the beta limit remains to be discovered experimentally (present beta limits may be limited by the ohmic input power or transport, rather than a stability limit), the instabilities which arise with a resistive shell remain to be thoroughly diagnosed and controlled, and techniques to sustain the plasma current must be developed.

Many fundamental questions remain in RFP dynamo and transport physics. Dynamo physics becomes richer as additional possible dynamo effects are explored. Transport reduction by current profile control has been dramatic; however, the present lower limit to transport likely only represents the limitations of the present, rather coarse, profile control techniques. The ultimate lower limit to magnetic fluctuations and transport is yet to be discovered.

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