ADVANCES AND PROSPECTS IN REVERSED FIELD PINCH RESEARCH

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ABSTRACT

The reactor attributes of the compact, high beta RFP are as needed today as when the RFP was conceived. Confinement is a dominant scientific issue at present. In the past several years magnetic fluctuations have been shown experimentally to drive anomalous transport. From an understanding of the cause of transport, it is expected that flattening of the current density profile should suppress fluctuations and transport. Inductive current profile control has succeeded in reducing fluctuations, and doubling the energy and particle confinement times. For steady state current profile control, electrostatic current injection (dc helicity injection) is under preparation and rf current drive (fast wave and lower hybrid) has been shown to be feasible.

I INTRODUCTION

The reversed field pinch (RFP) is an axisymmetric, current-carrying plasma with helical magnetic field. The toroidal field reverses direction near the edge of the plasma. On average, it is comparable in magnitude to the poloidal field. Thus, the RFP is similar to a tokamak with a very weak magnetic field. From the weak field follows reactor attributes that motivate RFP research: compactness, high power density, high beta, low field at the coils (the magnetic field decreases amplitude from the plasma toward the coils), free choice of aspect ratio, and absence of major disruptions. These attributes are as relevant today as when RFP research began, considering the large size and cost of present reactor designs.

To realize these reactor properties several RFP physics problems must be solved, particularly anomalous transport, conducting shell requirements, and current drive. Whereas all RFP experiments have operated at reactor relevant beta values ($> 5\%$), energy confinement is far from that required for a reactor (to date energy confinement time of 3 ms has been achieved). We consider confinement to be the

dominant RFP issue at present, and dedicate this report to recent significant progress and prospects in this area.

The main operating RFP experiments are RFX¹ in Padova, Italy, MST² in Madison, Wisconsin, TPE1RM-20³ and TPE-2M⁴ in Tsukuba, Japan, and T2⁵ in Stockholm, Sweden. The RFP program is well-integrated. RFX is a large RFP ($a = 0.45$ m, $R = 2$ m) with a goal of examining the scaling of confinement with current (the design current value is 2 MA with a duration of 0.25 sec; 0.8 MA has been achieved to date). MST is a large size RFP with moderate current (0.5 MA with about 80 ms duration) with a main goal of confinement improvement through current profile control. TPE1RM-20, TPE-2M and T2 have minor radii of about 0.2 m. The main goals of these experiments are confinement optimization, divertor studies, and resistive shell studies, respectively. In addition, a 1 MA experiment, TPE-RX, is beginning a staged construction in Tsukuba.

In recent years, a basic understanding of anomalous transport in the RFP may have been established through experiment and theory, as discussed in Section II. Based in this understanding, techniques have been developed to suppress the fluctuation-induced transport by current profile control. Initial attempts of inductive current profile control have succeeded in doubling the energy confinement time, described in Section III. Non-transient techniques of current profile control are being developed, such as electrostatic current injection and rf current drive, discussed in Section IV. A common confinement-degrading phenomenon in RFPs and tokamak is mode locking to magnetic field errors. Initial measurements of the correlation between fast changes in mode rotation and plasma rotation are discussed in Section V. Conclusions and prospects for the next few years are reviewed in Section VI.

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II THE CAUSE OF ANOMALOUS TRANSPORT

It has long been believed that anomalous transport in the RFP is produced by magnetic fluctuations. The magnetic fluctuations are well-understood to be current-driven, resistive MHD, tearing-type modes. There is excellent semi-quantitative agreement between resistive MHD computation and experiment in the magnetic fluctuations spectra and amplitude, the nonlinear three-wave mode coupling⁶ and the current density fluctuation amplitude and phase relations. The fluctuation spectrum is dominated by several $m=1$ modes resonant in the core, with an amplitude of about 1%. These global modes are mostly unaffected by addition of a divertor magnetic field.

Magnetic fluctuations can drive transport through particle motion along a stochastic magnetic field. For example, electron radial energy transport from magnetic fluctuations is identically given by $Q_{re} = \langle \delta Q_{||e} \delta B_r \rangle$, where $\delta Q_{||e}$ is the fluctuating heat flux parallel to the equilibrium field, and δB_r is the fluctuating radial field. Similarly, the radial electron particle flux driven by magnetic fluctuations is given by $\Gamma_{re} = \langle \delta j_{||e} \delta B_r \rangle$, where $\delta j_{||e}$ is the fluctuating parallel electron current density. In MST these ensemble averaged quantities have been measured in the outer 20% of the plasma ($\delta Q_{||e}$ by an insertable fast pyro-bolometer and $\delta j_{||e}$ by an electrostatic energy analyzer). The measured radial energy flux is shown in Figure 1 as a function of radius.⁷ In the "core" region ($r/a < 0.85$) the energy flux is large, about equal to the total energy flux. This is consistent with the expectation that this region is stochasticized by the core resonant modes. Contrariwise, in the extreme edge ($r/a > 0.85$) the energy flux is small, consistent with the expectation that this region is not stochastic since the dominant modes are not resonant in the edge. The particle flux from magnetic fluctuations displays the same properties.⁸ Hence, these results prove that magnetic fluctuations drive transport in the RFP within the reversal surface at $r/a = 0.85$ (within the limits of the radial range measured and the low current discharges employed).

Fig. 1: Magnetic fluctuation induced radial

electron energy flux $Q_r = \frac{\langle \delta Q_{||e} \delta B_r \rangle}{B}$ vs radius.

Correlation of the global confinement time with magnetic fluctuations has also been observed in TPE1RM-20, by varying the fluctuation amplitude (through a variation in pinch parameter).⁹ Past measurements have shown that electrostatic measurements drive particle flux at $r/a > 0.85$, but not significant energy flux. Hence, the present picture of RFP confinement, substantiated by experiment, is that core transport is from magnetic fluctuations and edge particle transport is from electrostatic fluctuations. The cause of edge energy transport is not yet determined.

III REDUCTION OF TRANSPORT BY INDUCTIVE CURRENT PROFILE CONTROL

From the above evidence regarding magnetic fluctuation induced transport, it is expected that current profile control (to reduce the current density gradient) should decrease the magnetic fluctuations and the associated transport. Hence, current profile control forms a scientifically based approach to confinement improvement. MHD computation indicates that appropriate flattening of the current profile reduces the fluctuations such that nested magnetic surfaces develop in a puncture plot that is otherwise stochastic.

For an initial, transient test of the concept a poloidal loop voltage pulse is applied during an MST discharge.¹⁰ The 10 volt pulse drives edge parallel current, flattening the profile roughly to

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the degree of flatness characteristic of the plasma immediately following a sawtooth crash. The current profile flattening eliminates the precursor growth of the magnetic fluctuations and their associated sawtooth oscillations. The time-averaged amplitude of magnetic fluctuations decreases by 25%.

The energy and particle confinement times double, as depicted in Figure 2. In the

Fig. 2: Electron density, Ion temperature, Ohmic input power and H_α emission with (solid curves and without (dashed) inductive current profile control. The voltage pulse is applied at 12 ms. Each curve is a multi-shot average.

comparison between shots with and without the extra current drive, it is seen that the voltage pulse leaves the stored energy roughly unchanged (or increased slightly), but halves the Ohmic power input (with the extra energy input of the poloidal loop voltage included). The Ohmic power reduction corresponds to a toroidal loop voltage reduction from about 15 V to 7 V. The confinement time increases from 0.9 ms to 2.2. ms. The particle confinement time increase is reflected in the halving of the H_α emission, indicative of a particle source reduction.

A related profile effect has been observed in the T1 experiment.¹¹ A comparison between discharges with different resistivity profiles indicates that magnetic fluctuations increase with

the peakedness of the profile. The magnetic fluctuation spectra, and their changes with resistivity profile peakedness, agrees remarkably well with predictions from nonlinear MHD computation. The interpretation is that with higher edge resistivity the fluctuations must increase to drive the edge current to sustain reversal.

IV STEADY STATE CURRENT PROFILE CONTROL TECHNIQUES

The doubling of confinement with transient, inductive current profile control is very encouraging. In addition, the calculated islands widths indicate that the plasma is near the island overlap threshold, below which the field stochasticity is expected to disappear. Hence, it is critical to optimize the effect to achieve a greater than two confinement improvement. To this end, two steady state current profile control techniques are planned : electrostatic current injection and rf current drive.

IVA Electrostatic Current Injection

MHD computation has demonstrated that electrostatic current injection (or "dc helicity injection") can flatten the profile to an extent that fluctuations reduce dramatically.¹² In this technique, current is injected into the edge plasma by producing an electrostatic potential drop along field lines which intercept an injector. In MST, an electrostatic current injection experiment is under construction for the purpose of confinement improvement. A novel injector has been developed in which electrons are extracted from a miniature plasma source (about 2 cm on a side) inserted into the edge plasma.¹³ The injector has high current emission (0.8 kA per injector) and, in contrast to material electrode emitters, produces very low impurity influx. For sufficient current injection for fluctuation suppression, it is estimated that about 30 injectors will have to be distributed toroidally around the device.

IVB RF Current Profile Control

Electrostatic current injection suffers from lack of controllability; it relies upon appropriate penetration of the edge current so that the profile

is adequately flattened. RF current drive offers the opportunity for controlled optimization of the current profile. Wave current drive theory developed for tokamaks is readily transferable to the RFP. However, there are several distinguishing features between the two configurations: the ratio ω_{pe}/ω_{ce} for the RFP is large (< 10 in the RFP, < 1 in the tokamak), the magnetic shear is strong, and the fraction of trapped particles is small.

Both fast wave¹⁴ and lower hybrid¹⁵ current drive have been studied theoretically and shown to be feasible for current profile control in the RFP. Accessibility, ray trajectories, and absorption have been calculated. As an example, a typical lower hybrid current drive scheme designed to drive current centered about $r/a = 0.7$ in present experiments could have a parallel refractive index of 10 and a frequency of $2f_{LH}$ or several hundred MHz. At present, no rf current drive experiments are authorized.

V MODE LOCKING AND PLASMA ROTATION

The locking of a rotating magnetic oscillation to a stationary field error is a process common to tokamaks and RFPs. In both cases it leads to confinement degradation. Although it is a controllable effect, and thus not a fundamental obstacle to RFP confinement, RFP experiments offer the opportunity to study the dynamics of mode locking, relevant to tokamaks and RFPs.

Two features in the MST permit study of the dynamics of mode locking: (1) an impulsive field error, with about a 100 μs risetime, is generated at the sawtooth crash by the sudden equilibrium shift, (2) a fast Doppler spectrometer has been developed to measure impurity ion flow velocity to 10 μs resolution.¹⁶ The observed locking sequence is that the impulsive field error first causes the rotating tearing mode to lock to the error, followed by a deceleration of the plasma in 100 μs . Thereafter the field error decreases (as the equilibrium diffuses to its original state), the plasma accelerates on a several ms timescale, followed by the unlocking of the mode. The locking has been interpreted using the model developed by Fitzpatrick and co-workers. The 100 μs slowdown time of the plasma is consistent with the inertial time due to

the electromagnetic torque exerted by the field error on the plasma (the solution to $r d\Omega/dt = \text{TEM}$, where Ω is the plasma rotation and TEM is the electromagnetic torque). The longer reacceleration timescale is about equal to a particle confinement time, presumably since the ambipolar electric field associated with rotation re-builds by particle diffusion. These studies are continuing.

VI SUMMARY

The reactor attributes of the RFP are as relevant today as when the RFP was conceived. The dominant physics issue at the present time is confinement. Experimental beta values are reactor-relevant, but confinement times are not. Substantial progress in confinement physics has occurred in recent years. A first principles understanding of anomalous transport may be in hand, through both experimental and theoretical progress. From this understanding, current profile control has been initiated as a means to suppress fluctuation-induced transport. Initial experiments with inductive current profile control have doubled the energy and particle confinement times. Current profile control by electrostatic injection is planned, and rf current drive (fast wave and lower hybrid) has been shown theoretically to be feasible.

As a result of this progress the RFP reactor concept appears, in a sense, to be more promising now than several years ago. The next 3 - 5 years promises significant new information. The international RFP program is small, but well-coordinated. In 3 - 5 years it should determine whether RFP confinement improves with plasma current (up to 2 MA), whether current profile control can significantly improve confinement, and whether a conducting shell is essential. We are also likely to have additional experimental information on current drive techniques and divertor effects. Hence, a stringent re-assessment of the RFP reactor prospects should be timely at the end of the decade.

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REFERENCES

1. G. Malesani and G. Rostagni, 14th SOFT, Avignon, 1, 173 (1986); also, Plasma Physics and Controlled Nuclear Fusion Research, Proc. 15th Int. Conf., Seville, paper IAEA-CN-6/C-1-I-2 (1994).
2. R.N. Dexter, D.W. Kerst, T.H. Lovell, S.C. Prager, and J.C. Sprott, Fus. Tech. **19**, 131 (1991).
3. Y. Yagi et al., Plasma Physics and Controlled Nuclear Fusion Research, Proc. 14th Int. Conf., Wurzburg, IAEA, Vienna **2**, 661 (1992).
4. K. Hayase, Y. Sato, K. Hattori, Intl Energy Agency RFP Workshop, Stockholm (1993).
5. J.R. Drake et al., Intl Energy Agency RFP Workshop, Stockholm (1993).
6. S. Assadi, S.C. Prager, and K.L. Sidikman, Phys. Rev. Lett. **69**, 281 (1992).
7. G. Fiksel, S.C. Prager, W. Shen and M. Stoneking, Phys. Rev. Lett. **72**, 1028 (1994).
8. M.R. Stoneking et al., Phys. Rev. Lett. **73**, 549 (1994).
9. Y. Yagi et al., Plasma Physics and Controlled Nuclear Fusion Research, Proc. 15th Int. Conf., Seville, IAEA, Vienna, paper IAEA-CN-60/C-1-I-3 (1994).
10. J.S. Sarff, S.A. Hokin, H. Ji, S.C. Prager, and C.R. Sovinec, Phys. Rev. Lett., **72**, 3670 (1994).
11. P. Nordlund et al., Plasma Physics and Controlled Nuclear Fusion Research, Proc. 15th Int. Conf., Seville, IAEA, Vienna, paper IAEA-CN-60/A6/C-P-6 (1994).
12. Y.L. Ho, Nucl. Fusion **31**, 341 (1991).
13. G. Fiksel et al., Bull. Am. Phys. Soc. **39**, 1620 (1994).
14. S. Shiina et al., Proc. of the 19th . on Controlled Fusion and Plasma Physics, European Physical Society, **17C**, 495 (1992).
15. E. Uchimoto et al., Plasma Physics **1**, 3517 (1994).
16. D.J. Den Hartog and R.J. Fonck, Rev. Sci. Inst. **65**, 3238 (1994).

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