INTERNATIONAL ATOMIC ENERGY AGENCY

17th IAEA Fusion Energy Conference
Yokohama, Japan, 19 - 24 October 1998

IAEA-F1-CN-69/EXP1/14

UNIFYING ROLE OF RADIAL ELECTRIC FIELD SHEAR IN THE CONFINEMENT TRENDS OF TRANSITIONLESS REGIMES IN TFTR

D. R. ERNST, S. BATHA,[1] M. BEER, M. G. BELL, R. E. BELL, R. V. BUDNY, B. COPPI,[2] W. M. DORLAND,[3] P. C. EFTHIMION, T. S. HAHM, G. W. HAMMETT, R. J. HAWRYLUK, K. W. HILL, M. KOTSCHENREUTHER,[4] F. M. LEVINTON,[1] Z. LIN, D. K. MANSFIELD, D. R. MIKKELSEN, R. NAZIKIAN, M. PORKOLAB,[2] G. REWOLDT, S. D. SCOTT, E. J. SYNAKOWSKI, M. C. ZARNSTORFF AND THE TFTR GROUP

Princeton Plasma Physics Laboratory,
Princeton University, Princeton, NJ 08543, USA

[1]Fusion Physics and Technology, Torrance, CA, USA

[2]Massachusetts Institute of Technology, Cambridge, MA, USA

[3]Institute for Plasma Research, University of Maryland, College Park, MD, USA

[4]Institute for Fusion Studies, University of Texas, Austin, TX, USA

UNIFYING ROLE OF RADIAL ELECTRIC FIELD SHEAR IN THE CONFINEMENT TRENDS OF TRANSITIONLESS REGIMES IN TFTR*

D. R. ERNST, S. BATHA,[1] M. BEER, M. G. BELL, R. E. BELL, R. V. BUDNY, B. COPPI,[2]
W. M. DORLAND,[3] P. C. EFTHIMION, T. S. HAHM, G. W. HAMMETT,
R. J. HAWRYLUK, K. W. HILL, M. KOTSCHENREUTHER,[4] F. M. LEVINTON,[1] Z. LIN,
D. K. MANSFIELD, R. NAZIKIAN, M. PORKOLAB,[2] G. REWOLDT, S. D. SCOTT,
E. J. SYNAKOWSKI, M. C. ZARNSTORFF AND THE TFTR GROUP
Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[1]Fusion Physics and Technology Inc., Torrance, California USA
[2]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[3]University of Maryland, College Park, Maryland, USA
[4]Institute for Fusion Studies, University of Texas-Austin, Texas, USA

Abstract

Turbulence suppression by radial electric field shear (E_r) is shown to be important in the enhanced confinement of TFTR supershot plasmas. Simulations of supershot ion temperature profiles are performed using an existing parameterization of transport due to toroidal ion temperature gradient modes, extended to include suppression by E_r shear. New spectroscopic measurements of E_r differ significantly from prior neoclassical estimates. Supershot temperature profiles appear to be consistent with a criterion describing near-complete turbulence suppression by intrinsically generated E_r shear. Helium spoiling and xenon puffing experiments are simulated to illustrate the role of E_r shear in the confinement changes observed.

1. INTRODUCTION

Advances toward understanding the confinement trends of transitionless enhanced confinement regimes, e.g., the TFTR supershot regime [1 ,2], as well as trends in L-Mode confinement have previously been described [3]. In these studies, an understanding of the role of radial electric field (E_r) shear in the confinement scalings of supershot and L-mode plasmas has emerged. A model for ion thermal transport, including an *intrinsically* generated E_r and allowing self-consistent evolution of the ion temperature and velocities, reproduces TFTR supershot ion temperature profiles under widely varying conditions. The results demonstrate that the ion temperature profile in the inner half-radius can be recovered from a simple criterion for suppression of turbulent cross-field transport. The criterion describes a self-regulating scenario in which near-complete suppression of turbulent transport is maintained by self-generated equilibrium E_r shear. In this paper, we will present recent progress in the simulation of transitionless, enhanced confinement TFTR supershot plasmas, with an emphasis on the role of E_r shear in observed confinement scalings.

The original model, developed prior to the availability of poloidal rotation measurements, employed a neoclassical calculation of the intrinsically generated flows driven by density and temperature gradients, using the model of Ref. [4] to parameterize toroidal ITG modes. New poloidal rotation measurements in TFTR [5], however, indicate a significant discrepancy with standard neoclassical results in both supershots and reverse shear plasmas. The E_r shearing rate derived from spectroscopically measured quantities is typically a factor of two larger than that derived using neoclassical [6] poloidal flows, with a profile peaked more closely to the magnetic axis. When the toroidal rotation is large, the measured and neoclassical E_r profiles are qualitatively similar, masking the difference. However, TFTR supershot cases with balanced tangential neutral beam injection reveal a significant discrepancy between neoclassical and measured poloidal velocities, resulting in very different E_r profiles. Nevertheless, when the measured poloidal rotation, rather than the neoclassical calculation, is used, the simulated core ion temperatures remain consistent with the same overall turbulence suppression criterion. While the previous turbulence suppression criterion appears to be preserved using the new measurements, the threshold condition for the suppression to occur has to be adjusted to compensate for the increased shearing rate. This adjustment is within the accuracy of the numerical simulations which form the basis for the criterion [7]. The dependence of this approach on

* Work supported by U.S. Department of Energy Contract no. DE-AC02-76CH03073.

measured poloidal rotation data, however, eliminates the predictive capability of the original model. The measured poloidal rotation, which is in the ion diamagnetic direction, is much larger than the neoclassical value and increases almost linearly with the ion temperature. Using this empirical characterization of the measured poloidal rotation, it has been possible to simulate the ion temperature profiles of some earlier experiments in TFTR for which poloidal rotation data is not available.

2. DESCRIPTION OF MODEL

The approach currently employed extends the parameterization of Ref. [4] describing ion thermal transport from toroidal ion temperature gradient driven modes [8] to include the effect of E_r shear suppression using a parameterization based on the results of nonlinear flux-tube gyrofluid calculations [7], which show that turbulent transport is completely suppressed according to the criterion that the E_r shearing rate for isotropic turbulence $\omega_{E\times B}$ [9] exceed the linear growth rate of the most unstable mode γ_{lin}^{max}. The expression for the ion thermal diffusivity in the presence of flow shear is taken as:

$$\chi_i = \chi_i^{IFS-PPL}(1 - \alpha_E|\omega_{E\times B}|/\gamma_{lin}^{max}) \times H(1 - \alpha_E|\omega_{E\times B}|/\gamma_{lin}^{max})$$

where H is the Heaviside step function, and α_E is a constant between 0.5 and 1.0. The carbon radial force balance equation is used to obtain E_r from spectroscopically measured quantities [5]. The ion temperature profile is evolved in a simulation code using density and power deposition profiles. from the TRANSP code. Because the simulations generally converge to $\alpha_E\omega_{E\times B} \simeq \gamma_{lin}^{max}$ in the core, T_i is insensitive to χ_i there. Further, the effect of varying α_E over the specified range is usually not qualitatively significant, as shown in Fig. 1(a), although adjustment is sometimes required for convergence.

3. HELIUM SPOILING OF SUPERSHOT PLASMAS

Supershot performance is strongly inversely correlated with the edge particle recycling. Because helium is not adsorbed by the carbon graphite tiles on the inner wall limiter surface, brief helium gas puffs result in lingering increases in the edge recycling rate. Relatively small puffs bring the energy confinement time of supershots to L-Mode levels in approximately one confinement time, without significant dilution of the hydrogenic mixture. Figure 1 shows that the model reproduces the drastic reduction in the ion temperature from 30 keV to 8 keV caused by a helium puff at 3.5 seconds (the neutral beam power was constant from 2.5-4.5 sec, while the confinement time dropped from 175 to 86 ms). Accordingly, the model spans the range of performance from supershot to degraded

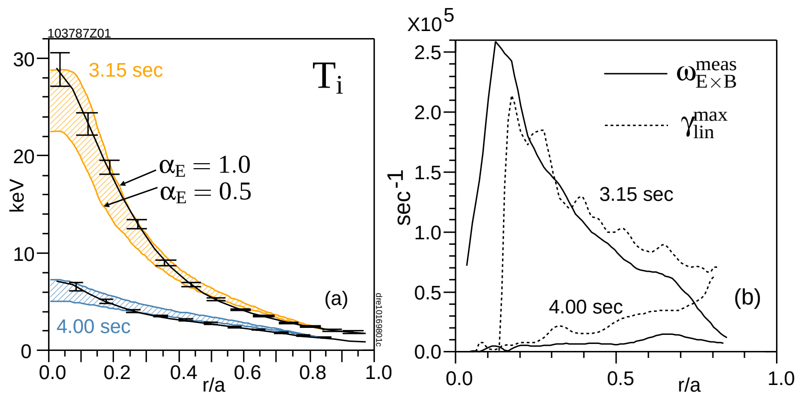

Fig. 1. Simulation of supershot helium spoiling experiment. Frame (a) compares simulated and measured carbon ion temperatures (shown with error bars) in equilibrium before and after the helium puff. The shaded regions show the effect of varying the coefficient α_E over the range from 0.5 to 1.0 as required to more accurately reproduce some measured temperature profiles. Frame (b) compares the E_r shearing rate and toroidal ITG mode maximum linear growth rate, computed during the nonlinear simulations, before and after the helium puff.

confinement. Frame (b) shows the computed growth rate and measured shearing rate before and after the puff. In the supershot phase preceding the puff, the turbulence suppression criterion $\alpha_E \omega_{E\times B} \simeq \gamma_{lin}^{max}$ is approximately satisfied in the inner half-radius. After the puff, both the growth rate and shearing rate are much smaller, corresponding to toroidal ITG marginal stability in the absence of sheared flows.

4. ROLE OF E_r SHEAR IN PARADOXICAL CONFINEMENT IMPROVEMENTS

Figure 2 shows simulations of the ion temperature profiles comparing nearly consecutive discharges, one with 75% radiated power produced by xenon puffing, the other with no xenon. As described in Ref. [10], a significant improvement in both electron particle and ion thermal confinement is observed over most of the plasma cross-section, while the electron temperature remains surprisingly unchanged. Even without radial electric field shear, the model of Ref. [4] produces a small increase in T_i with xenon puffing, due to the more peaked electron density profile, the 10% increase in edge T_i, and possible stabilization by dilution. It is plausible that high-Z impurities have additional stabilizing influences through kinetic effects which are not in the parameterization. The influence of trapped electrons on toroidal modes with even up-down parity is not well-described, so that measured, rather than predicted density profiles are used. In this experiment, an increase in E_r was measured near the plasma edge following the xenon puff, which may be associated with the improved particle confinement. The reduced recycling observed can lead to reinforcing improvements in thermal energy and particle confinement through E_r shear. When E_r shear is included in the simulation (taking α_E=0.5), the simulated ion temperature rises a factor of two to reach agreement with the measured profile. In addition, the improvement associated with xenon is magnified to reproduce the large observed increase in central T_i. This amplification of improvements by radial electric field shear is typical and may underlie the mutually reinforcing character of supershot confinement scalings. Frame (b) of Fig. 2 shows that the simulated growth rate converges to the measured shearing rate in the inner half-radius, consistent with near-complete suppression of turbulent transport according to the criterion $\alpha_E \omega_{E\times B} \simeq \gamma_{lin}^{max}$. In the outer half-radius, the growth rate diverges from the shearing rate, corresponding to a monotonically increasing ion thermal diffusivity profile as in L-Mode plasmas. The measured E_r shearing rate for the xenon case is larger over most of the cross-section than in the baseline discharge.

Strong improvements in ion thermal confinement are also observed in tritium plasmas, consistent with a global energy confinement time scaling $\tau_E \propto A_i^{0.89}$ [11], where is the average thermal hydrogenic mass. This is much stronger than scalings of at most $\tau_E \propto A_i^{1/2}$ previously observed for mixtures of hydrogen and deuterium. Using the empirical expression for the carbon poloidal rotation, $v_\theta = \alpha_{T\theta} T_i$, where $\alpha_{T\theta} \simeq 1.0$ km/sec/keV [5], together with the approximation

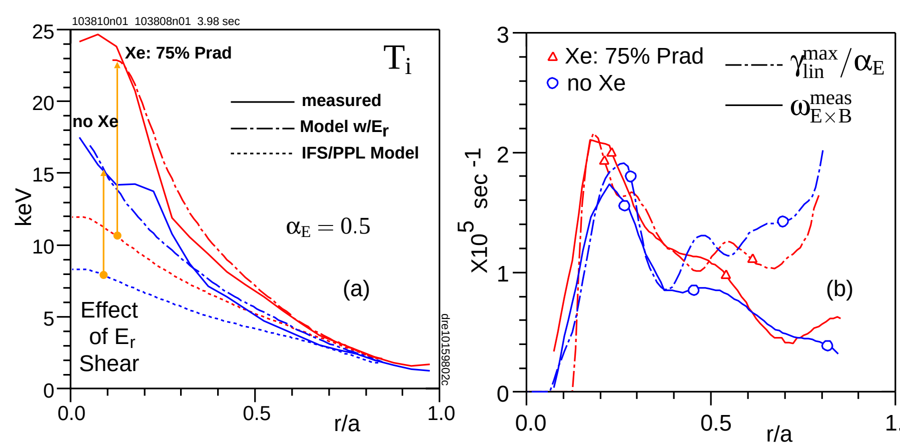

Fig. 2. Carbon ion temperatures for the Xe comparison pair, simulated by a model describing toroidal ion temperature gradient driven modes both with and without E_r shear suppression. A stabilizing effect of Xe is apparent even without E_r shear and is strengthened when E_r shear is included, bringing simulated and measured temperatures into agreement.

$\gamma_{lin}^{max} \simeq (T_e/4T_i)(1/L_T - 1/L_T^{crit})(T_i/m_i)^{1/2}$ [4], where L_T^{crit} is the toroidal ITG critical temperature gradient scale length, and $\omega_{E\times B} \sim \alpha_{T\theta} T_i/L_T$ at high temperatures for quasi-balanced beam injection, an equation $L_T = L_T^{crit} \times \{1 - \alpha_E (4T_i/T_e)(\alpha_{T\theta}/310)\sqrt{T_i(keV)A_i}\}^{-1}$ for the ion temperature gradient scale length L_T can be found. This suggests that, not only will there be a favorable scaling with isotopic mass, but that E_r shear will play a stronger role at higher ion temperatures. Preliminary simulations of deuterium-tritium discharges using measured poloidal rotation appear to recover much of the DT supershot isotope effect. Further, this equation can be directly integrated inward from the half-radius to recover the ion temperature profile.

5. SUMMARY AND CONCLUSIONS

We have demonstrated that the ion temperature profiles of TFTR supershot plasmas are consistent with a model for turbulence suppression by intrinsically generated E_r shear. While successful, this model is based, however, on criteria which are not rigorously derived, but loosely supported by the results of numerical simulations. Further, we have made several approximations, such as neglecting trapped electrons, to provide a simplified and tractable description.

Although the results suggest that E_r shear is an important influence on core ion thermal confinement in supershot plasmas, there is little direct experimental evidence for the role of E_r shear in suppressing turbulence, as reviewed in Ref. [12]. Some of the strongest evidence has been obtained from controlled experiments in TFTR L-Mode plasmas which systematically varied the toroidal rotation [3]. These data support the proposed role of intrinsically generated E_r shear in enhanced confinement regimes without transitions. It should be noted that the discrepancy between measured and neoclassical poloidal rotation is suggestive, in several respects [2], of turbulence-generated flows [13]. A theoretical understanding of this phenomenon could provide a fundamental basis for the model and results presented here, and may reveal parametric dependences of L_T not described by the TFTR poloidal rotation dataset.

REFERENCES

[1] ERNST, D. R., Ph.D. thesis, Physics Dept., Mass. Inst. of Technology, 1997.

[2] ERNST, D. R. *et al.,* Phys. Rev. Lett. **81** (1998) 2454.

[3] BATHA, S. *et al.*, in Proc. 24th EPS Conference on Contr. Fusion and Plasma Physics, Bournemouth, UK (European Physical Society, Petit-Lancy, Switzerland, 1997).

[4] KOTSCHENREUTHER, M., DORLAND, W. M., BEER, M., AND HAMMETT, G. W., Phys. Plasmas **2** (1995) 2381.

[5] BELL, R. E. *et al*., this conference, paper IAEA-CN-69/EXP1/13 (R).

[6] ERNST, D. R. *et al.*, Phys. Plasmas **5** (1998) 665.

[7] WALTZ, R. E., KERBEL, G. D., AND MILOVICH, J., Phys. Plasmas **1** (1994) 2229.

[8] COPPI, B. AND PEGORARO, F., Nucl. Fusion **17** (1977) 969.

[9] HAHM, T. S., AND BURRELL, K. H., Phys. Plasmas **2** (1995) 1648;
BIGLARI, H., DIAMOND, P. H., AND TERRY, P. W., Phys. Fluids B **2** (1990) 1.

[10] HILL, K. W. *et al*., this conference, paper IAEA-CN-69/EXP2/12.

[11] SCOTT, S. D., ERNST, D. R., MURAKAMI, M. *et al*., Phys. Scr. **51** (1995) 394;
ZARNSTORFF, M. *et al*., in Plasma Physics and Controlled Nuclear Fusion Research, 1996 (International Atomic Energy Agency, Vienna, 1998) pp. 573-591.

[12] BURRELL, K.H., Phys. Plasmas **4** (1997) 1499.

[13] HASEGAWA, A., AND WAKATANI, M., Phys. Rev. Lett. **59** (1987) 1581;
DIAMOND, P.H., AND KIM, Y.-B., Phys. Fluids B **3** (7) (1991) 1626;
ROSENBLUTH, M.N., AND HINTON, F.L., Phys. Rev. Lett. **80** (1998) 724.