GA–A23419

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T.L. RHODES,* J.-N. LEBOEUF,* R. SYDORA,† E.J. DOYLE,*
R.A. MOYER,‡ C.L. RETTIG,* K.H. BURRELL, D.M. THOMAS,
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This is a preprint of a paper presented at the 27th European Physical Society Conference on Controlled Fusion and Plasma Physics, June 12–16, 2000 in Budapest, Hungary and to be published in the *Proceedings.*

*University of California, Los Angeles, California
†University of Alberta, Canada
‡University of California, San Diego, California
◊University of Wisconsin, Madison, Wisconsin

Work supported by
the U.S. Department of Energy under Contract No. DE-AC03-99ER54463, and
Grant Nos. DE-FG03-86ER53225, DE-FG03-95ER54292, DE-FG03-96ER54373

GA PROJECT 30033
AUGUST 2000

Turbulent radial correlation lengths in the DIII–D tokamak

T.L. Rhodes,[1] J.-N. Leboeuf,[1] R. Sydora,[2] E.J. Doyle,[1] R.A. Moyer,[3]
C.L. Rettig,[1] K.H. Burrell,[4] D.M. Thomas,[4] G.R. McKee,[5] W.A. Peebles[1]

[1]*Electrical Engineering and Physics Depts., UCLA, Los Angeles, California 90025*
[2]*Physics Dept, University of Alberta, Canada*
[3]*FERP, University of California, San Diego, California*
[4]*General Atomics, P.O. Box 85608, San Diego, California*
[5]*University of Wisconsin, Madison, Wisconsin*

Abstract — Measurements of the radial correlation length Δr of density fluctuations have been made on the DIII–D tokamak in a variety of L–mode discharges. These measurements span the radial region $0.5 < \rho \leq 1$ and are found to scale approximately as $\rho_{\theta,s}$ or 5-10 ρ_s. Here $\rho_{\theta,s}$ is the poloidal ion Larmor radius calculated using local T_e and poloidal magnetic field and ρ_s is the same except calculated using the total magnetic field. The Δr data were obtained from a heterodyne reflectometer system. Comparisons to published analytic formulas of Δr have been carried out for a particular discharge condition. The measurements are found to be comparable in magnitude and radial dependence with a slab type formulation of ion temperature gradient (ITG) driven turbulence as well as an electron drift wave turbulence type prediction. Predictions from toroidal ITG and a different slab ITG model were found to be outside the error bars of the measurements. In addition, a detailed comparison to a non-linear gyro-kinetic turbulence code has begun. These and other similar comparisons are believed to be important as they serve to test and benchmark theory and codes as well as to help identify the type(s) of turbulence involved.

The understanding and control of heat and particle transport in fusion plasmas is a problem of longstanding interest. This transport is often larger than predictions based upon collisionallity treatments and the primary suspect is turbulence or instability induced transport. A large amount of progress has been made in this area by many experimentalists and theorists, however the underlying instabilities have yet to be conclusively identified. This is in part due to the difficulty in making experimental measurements and in part to the probability that more than one type of instability may be active at any given condition. This paper presents a brief report of further work in this area that is ongoing at the DIII–D tokamak. In particular, experimentally measured correlation lengths are compared to analytical predictions and a numerical turbulence simulation. Similarity in magnitude and radial behavior is found between the measurements and some of the analytical predictions and the simulation.

The experiments reported here were carried out on the DIII–D tokamak with the following plasma parameters: major radius 1.67 m, minor radius 0.65 m, vertical elongation ~1.8, plasma current 1.5 MA, central magnetic field 2.1 T, injected neutral beam power of ~7.5 MW, and chord averaged density ~ 3×10^{13} cm^{-3}. An L–mode plasma was utilized and the effects of sawteeth were avoided by suppressing them via early neutral beam injection. Radial correlation length data were obtained using a heterodyne correlation reflectometer (see Ref. [1] for a system description and the references therein for the technique). This is a frequency tunable system (50–75 GHz) capable of accessing a large portion of the discharge. The 1/e point of the cross-correlation function of radially separated points is used to define Δr in the experimental as well as in the numerical simulation. For radial positions $\rho < 0.9$ the plasma parameters of interest for various instability regimes are: normalized plasma collisionallity $\nu_e^* = (\nu_{ei} R)/(r\omega_{bounce}) < 1$; $\tau = T_e/T_i \approx 0.75$; and $\eta_i = L_n/L_{Ti} \geq 1.5$. Here r = tokamak minor radius, R = tokamak major radius, ω_{bounce}= trapped electron bounce frequency, ν_{ei} the electron-ion collision frequency. For the data shown here, the plasma is in a regime relevant to the trapped electron mode (for $\rho < 0.9$), the collisionless drift wave ($0.9 < \rho < 1$), and the ITG mode ($\rho < 1$). The reader is referred to Ref. [2] for a discussion of the relevant electron mode regimes and Ref. [3] for a numerical survey of ITG linear stability parameters.

It is found that in L–mode and ohmic plasmas radial correlation lengths Δr generally increase from approximately 0.5 cm at the edge to as much as 3–4 cm at ρ ~0.2–0.3. Note that this statement does not hold for the central core of negative central shear plasmas and the edge of H–mode plasmas where Δr is typically shorter than similar radial locations in L–mode. The L–mode behavior is illustrated in Fig. 1 which shows Δr taken from the set of L–mode discharges described above. The measure-ments span a large part of the plasma radius, covering the radial locations ρ = 0.45–1.0. Also shown are estimates of ρ_i, $\rho_{\theta,i}$, ρ_s, and $\rho_{\theta,s}$ which are the ion gyroradius, ion poloidal gyroradius, the ion sound gyroradius (i.e. the ion gyroradius calculated using the electron temperature) and the ion sound poloidal gyroradius respectively. These gyro-radii values are significant as they enter into the theoretical predictions of the radial correlation lengths (they are generally related to the mode width of the instability). The gyro-radii are calculated using ECE and Thomson scattering measurements of T_e, CER measurements of T_i, with the magnetic field from magnetic probes and the equilibrium fitting routine EFIT. It is observed that the measured Δr are 5–10 times larger than either ρ_s or ρ_i but are of order the poloidal gyroradii $\rho_{\theta,i}$ or $\rho_{\theta,s}$. Note that many simulations indicate a radial correlation length in the numerical range $\Delta r \approx$ 5–10 ρ_s [3–7]. Currently, the two scalings ($\rho_{\theta,s}$ or 5–10 ρ_s) are not distinguishable due to error bars inherent in the various measurements. These observations are typical of DIII–D L–mode conditions. That is, while numerical values may differ, the general behavior of increasing values towards the center, and magnitude of order $\rho_{\theta,s}$ or 5-10 times larger than ρ_s is generally observed.

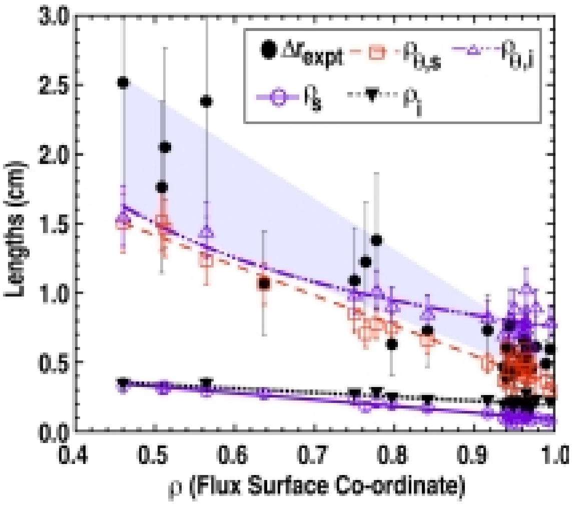

Fig. 1. Showing measured Δr, ρ_s, ρ_i, $\rho_{\theta,i}$ and $\rho_{\theta,s}$. The shaded portion indicated 5–8 times ρ_s.

Figures 2 and 3 compare the experimental turbulent correlation lengths from Fig. 1 to various analytical predictions of the radial correlation length. Figure 2 shows a comparison to analytical predictions of Δr for the following: Δr (slab ITG) [8] = $\rho_s\,[(1+\eta_i)/\tau]^{1/2}$, Δr (slab ITG) [9] = $\rho_s\,[qR(1+\eta_i)/(s_{hat}\tau L_n)]^{1/2}$, Δr (toroidal ITG) [9,10]) = $\rho_s\,[(q/s_{hat})^2 R\,(1+\eta_i)/(\tau\, 2 L_n)]^{1/4}$, and Δr (neo-classical ITG) [11] = $\rho_{\theta,s}\,(1+\eta_i)^{1/2}$. The parameters of interest used in these formulas are: $\eta_i = d\,ln(T_i)/d\,ln(n_i)$, $s_{hat} = d\,ln(q)/d\,ln(r)$ the magnetic shear parameter, $L_s = Rq/s_{hat}$ the magnetic shear length, T_i is the ion temperature, n_i the ion density (the electron density n_e is used for this study), $L_n^{-1} = d\,ln(n_e)/dr$ the density profile scale length, q the magnetic safety parameter, r the minor radius, and R the major radius. All of the analytical ITG estimates shown predict a general increase in Δr with decreasing radius similar to the experimental measurements. However, only the slab ITG estimate [9] and the neo-classical ITG [11] are numerically close (note that the neo-classical ITG is likely relevant only near the edge ρ>0.9 where the collisionality is higher). Figure 3 shows a comparison of the data to the predictions of electron drift wave turbulence. There is a general increase with decreasing radius in a manner similar to both the ITG predictions and the experimental data. The experimental values of Δr are similar to $x_i = (L_s/L_n)(T_e/T_i)^{1/2}\rho_s$, where x_i is the inverse width of the turbulent drift wave wavenumber spectrum [12]. Comparisons have also been made to correlation lengths that have been termed "mesoscale", that is intermediate between the scale size of the machine and that of the microturbulence [7,13,14]. These scales can arise in the linear stage of turbulence development [6] or due to the constructive interference of many

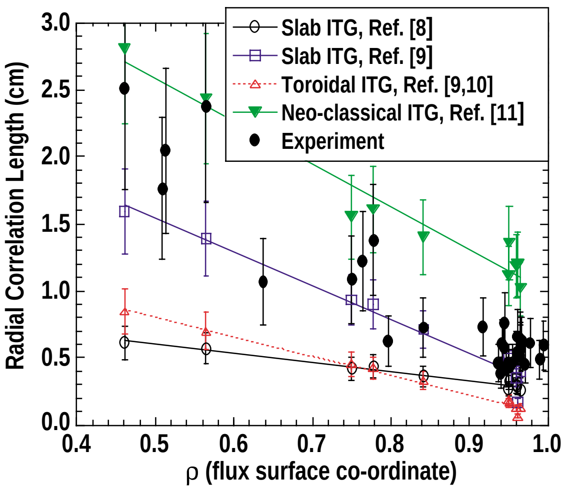

Fig. 2. Measured Δr and ITG predictions.

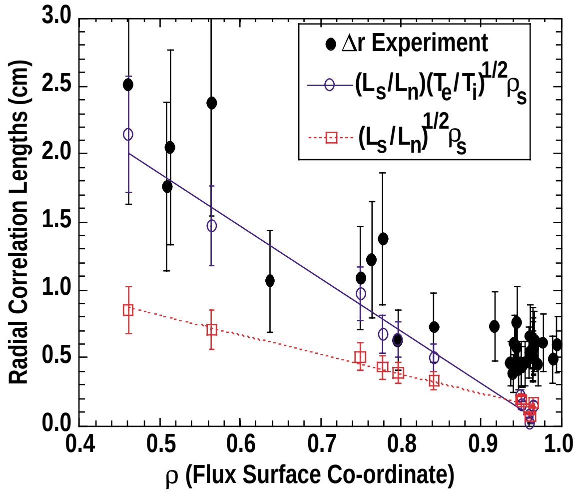

Fig. 3. Measured Δr and drift wave predications.

micromodes [13]. Although not shown here (due to space constraints the data will be shown in a later paper) the experimental data are similar to the predictions of a mesoscale type $\Delta r \approx (\rho_i L_{Ti}/s_{hat})^{1/2}$ (Ref. [6]).

We turn now to results from an initial comparison between experiment and numerical turbulence simulation (Fig. 4). This is the beginning of a broad comparison of turbulence and other parameters (Δr to start, then spectra, fluctuation levels, etc. from various diagnostics as appropriate) to code predictions [15]. The simulation was carried out using the three-dimensional toroidal electrostatic gyro-kinetic code described in Ref. [7]. Experimental inputs to the code were the measured n_e, T_i, and q profiles. Two different numerical runs are shown, one without zonal or self-generated flows and one with zonal flows. Without the zonal flows the Δr are very long, spanning a good portion of the approximately 65 cm minor radius. With zonal flows the numerically determined lengths drop to near the measured Δr. While this agreement is intriguing it should be pointed out that this is a very early stage of the comparison and more work remains. For example, the plasmas simulated are circular while the real plasmas were shaped (although the other parameters, n_e, T_i, q, etc., were matched as closely as possible). A fully shaped code is currently being utilized and broader, more complete comparisons are in progress. These results do demonstrate the potential benefits and have laid the ground work necessary for future comparisons.

In summary, correlation lengths for DIII–D L–mode plasmas are observed to increase from approximately 0.5 cm at the edge to as much as 4 cm in the deep core plasma. The measured Δr are found to be significantly larger than ρ_s by a factor of 5 to 10. The observed trend of increasing Δr with decreasing radius is similar to the trends predicted by all the analytical estimates examined here. In magnitude and radial behavior, the core Δr (ρ< 0.9) are comparable to (i.e. within error bars) a slab ITG [9] and electron drift wave [12] turbulence predictions. Note that these are quite different instabilities. The analytical estimates of correlation length for slab ITG of Ref. [8] and toroidal ITG [9,10] turbulence are generally below the measured Δr. Near the edge (ρ> 0.9) only the neo-classical ITG [11] and slab ITG [9] appear to have the correct magnitude. The measured Δr are similar to at least one prediction of mesoscale [6] like Δr. It should be pointed out that even predictions that don't agree can be brought into agreement via an undetermined constant multiplier on the theoretical value. It is found that the measured correlation lengths tend to follow the scaling and magnitude of the local value of poloidal sound gyroradius $\rho_{\theta,s}$ (Fig. 1). This may simply be a correlation without any direct relation but it deserves further investigation. Experiments are planned to differentiate between a ρ_s and a $\rho_{\theta,s}$ scaling as well as between other scalings.

For example, the difference between slab ITG [9] Δr_{ITG} and electron drift wave [12] Δr_{DW} can be characterized by the ratio $\Delta r_{ITG}/\Delta r_{DW} \approx (L_n/L_s)^{1/2} (T_i/T_e) (1+\eta_i)^{1/2}$. This suggests an experiment varying the ratio (T_i/T_e), keeping other variables constant. A somewhat different approach involves a close comparison with numerical turbulence simulations. These numerical plasmas are being diagnosed with 'numerical instruments' that simulate as closely as possible the real diagnostics using equivalent data analysis techniques. In this manner the comparison between the simulation and the measurements will be as consistent and as close as possible. This work is currently underway.

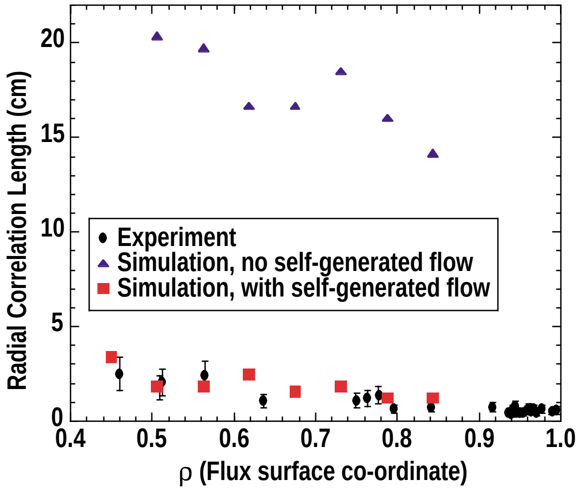

Fig. 4. Measured Δr and numerical simulations.

In conclusion, measurements of turbulence correlation length provide a yardstick for comparison to theory and simulation. These and other similar comparisons are believed to be important as they serve to test and benchmark theory and codes as well as to help identify the type(s) of turbulence involved. That the measured Δr are not significantly different from two different types of turbulence (ITG and electron drift wave) is perhaps significant, indicating that the two could be co-existent within the plasma.

This work was supported by the U.S. Department of Energy under Grants DE-FG03-86-ER53225, DE-FG03-95ER54294, DE-FG03-96ER54373, and Contract DE-AC03-99ER54463.

[1] T.L. Rhodes, *et al.*, Rev. Sci. Instrum., **63** 4661 (1992).
[2] Wendell Horton, Jr., Phys. Fluids **19** 711 (1976).
[3] J.Q. Dong, W. Horton, and J.Y. Kim, Phys. Fluids B **4** 1867 (1992).
[4] R.E. Waltz, *et al.*, Phys.Plasmas **2** 2408 (1995).
[5] S.E. Parker, W.W. Lee, and R.A. Santoro Phys. Rev. Lettr. **71** 2042 (1993).
[6] G. Furnish, *et al.*, Phys. Plasmas **6** 1227 (1999).
[7] R.D. Sydora, V.K. Decyk, and J.M. Dawson, Plasma Phys. Control. Fusion **38** A281 (1996).
[8] G.S. Lee and P.H. Diamond, Phys. Fluids **29** 3291 (1986).
[9] H. Biglari, P.H. Diamond, and M.N. Rosenbluth, Phys. Fluids B **1** 109 (1989).
[10] Wendell Horton, Jr. Duk-In Choi, W.M. Tang, Phys. Fluids **24** 1077 (1981).
[11] Y.B. Kim, *et al.*, Phys. Fluids B **3** 384 (1991).
[12] F.Y. Gang, P.H. Diamond, and M.N. Rosenbluth, Phys. Fluids B **3** 68 (1991).
[13] W. Horton, Rev. of Modern Physics **71** 735 (1999).
[14] T.S. Hahm and W.M. Tang, Phys. Plasmas **3** 242 (1996).
[15] J-N. Leboeuf, *et al.*, Phys. of Plasmas **7** 1795 (2000).