Quantitative Comparisons of DIII–D Turbulence Measurements to Gyro-Kinetic and Gyro-Fluid Turbulence Simulations

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Abstract. Experimental turbulence and transport characteristics in DIII–D plasmas have been compared with similar quantities calculated from gyro-kinetic and gyro-fluid turbulence simulations. Turbulent radial correlation lengths Δr from DIII–D L–mode plasmas scale as 5 to 10 ρ_s (ρ_s = ion gyro-radius evaluated using the electron temperature) and are independent of the poloidal magnetic field. Comparisons to a global gyro-kinetic code (UCAN) show similar behavior (i.e. magnitude, radial scaling, lack of B_θ dependence) when zonal flows are included. Experimental Δr from quiescent double barrier (QDB) plasmas show both a reduction below this L–mode scaling, consistent with reduced core transport, as well as similarities with UCAN simulations of Δr. Gyro-fluid flux tube simulations (GRYFFIN) of L–mode discharges have likewise been performed and comparisons show similarities between measured and simulated poloidal wave number spectrum while the simulated ion thermal transport and density fluctuation levels are larger than experiment by factors of ~1.5 and ~4 respectively.

1. Introduction

Comparison of experiment and direct numerical simulations of plasma turbulence are timely and important since simulation capabilities have increased to the point where they are being used in the design and interpretation of experiments and are anticipated for use in the design of future machines. A central idea underlying such a comparison is the implementation of numerical diagnostics that simulate real world experimental measurements and analysis techniques. The diagnostics simulated within the codes need similar localization (or lack thereof as in chord averaged measurements), wavenumber and frequency response, detection position within the plasma, as well as similar data analysis techniques, normalizations, use of 1/e points versus 1/2 power points, etc. A listing of the turbulence diagnostics on DIII–D which are either currently available or planned for the near future is shown in Table I. Indicated there is the fluctuating quantity a particular diagnostic measures (e.g. density or temperature fluctuations) as well as the derived quantities or moments (e.g. poloidal wavenumber spectrum). Of note is that the majority of diagnostics look at density fluctuations with only a few able to measure temperature, magnetic fluctuations, etc. This list does not include all possible diagnostics, rather, only those available now or in the near future on the DIII–D tokamak. Also shown are some example limitations for each diagnostic which illustrates that although two diagnostics might measure comparable quantities their simulation can be very different. It also points to the desirable situation where more than one type of diagnostic measures similar parameters. From Table I it can been seen that it is not only the fluctuation levels, e.g. ñ, that are available but also wavenumber spectra, dispersion characteristics, and direction of propagation within the plasma. At DIII–D the initial experiment-simulation comparison process is being carried out using turbulent radial correlation lengths, power spectra, fluctuation levels, and transport fluxes. The simulation codes compared to in this paper are UCAN, a global gyro-kinetic particle-in-cell code [1]; GRYFFIN, a gyro-Landau-fluid flux tube code [2]; GS2, a gyro-kinetic flux tube code with full shaping [3]; and GYRO, a non-linear Eulerian gyrokinetic-Maxwell code [4]. These experimental-simulation comparisons can set the framework and develop the tools necessary for both current and future comparisons. Presented in the next section are experimental measurements and their comparison to results from turbulence simulation codes.

Table I. Current and near future DIII-D turbulence diagnostics.

FIR scattering	Chord average dependent	ñ, k_θ
PCI (phase contrast imaging)	Chord averaged	ñ, Δr
BES (beam emission spectroscopy)	Needs NBI	ñ/n, Δr, k_θ, V_θ, τ_c, zonal flow
Reflectometry	Location is profile dependent	ñ, Δr, k_θ, V_θ
ECE (electron cyclotron emission)	Spot size depends upon optics, long time average	$\tilde{T}$, k_θ, V_θ
Langmuir probes	Edge plasma	ñ, $\tilde{T}$, $\tilde{\phi}$, Γ, Q, k_θ, V_θ
Magnetic probes	Edge plasma	$\tilde{B}$, $k_{\|\|}$, k_θ
Polarimetry (future)	Chord averaged	$\tilde{B}$
High-k scattering (future)	Under development	ñ, k >10 cm^{-1}, $k\rho_s > 1$

2. Comparisons of Experimental and Simulated Turbulence Quantities

Experimentally, turbulent radial correlation lengths Δr from DIII–D L–mode plasmas are observed to increase from approximately 1 cm at the edge to as much as 4 cm in the deep core plasma. These measurements were made using a frequency tunable (50–75 GHz) correlation reflectometer system [5] as well as a beam emission spectroscopy (BES) system [6]. Both systems make measurements near the plasma midplane on the low field side. The correlation length is a statistical quantity which is independent of amplitude, thus avoiding some potential calibration issues and making it an excellent candidate for quantitative comparison to simulation. This helpful feature also holds true for similar quantities such as the shape of wavenumber spectra, auto- and cross-correlation times, etc. In Ohmic and L–mode plasmas the measured Δr are found to be significantly larger than ρ_s (the ion gyro-radius evaluated using the electron temperature) by a factor of 5 to 10 (Fig. 1). The observed trend of increasing Δr with decreasing radius is similar to the trends predicted by several analytical estimates (i.e. ITG, electron drift wave) as well as some meso-scale type correlation lengths [7]. For Ohmic and L–mode plasmas the experimental Δr were numerically close to both 5-10 ρ_s (here ρ_s = ion gyro-radius evaluated using the electron temperature) as well as the poloidal gyro-radius $\rho_{\theta,s}$ ($\rho_{\theta,s} = \rho_s B_{tot}/B_\theta$). This presented an interesting question since a scaling with $\rho_{\theta,s}$ might have been indicative of a dependence on the trapped ions via the banana orbit width and/or a plasma current dependence. Previous work found that Δr scaled as the normalized ion gyro-radius ρ* ($\rho^*=\rho_i/a$) [8] however that experiment was performed by varying the toroidal field B_z while keeping the ratio B_z/B_θ constant. Since B_θ and B_z varied in the same proportion a B_θ dependence would not be distinguished from a B_z dependence. Consequently an experiment was designed and performed to break this indeterminacy and to determine if Δr scaled with $\rho_{\theta,s}$. It was found that Δr did not scale with $\rho_{\theta,s}$ (Fig. 2) indicating the scaling seen previously [8] was due to ρ*.

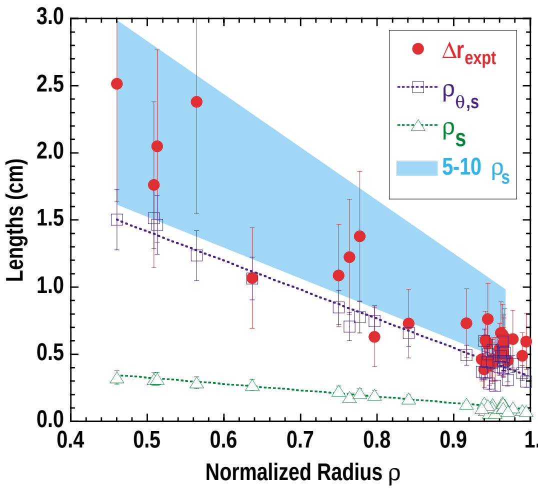

Fig. 1. Experimental radial correlation lengths and various gyro-radii from L–mode plasma showing typical radial dependence as well as Δr magnitude in range 5–10 ρ_s.

Comparisons have been made to the UCAN code which is a massively parallel, nonlinear, toroidal, 3-D, global gyrokinetic particle-in-cell code developed at UCLA [1]. For the calculations presented here, a circular cross section, adiabatic electrons, and zero plasma β were used. Polynomial fits to the experimental profiles for temperatures, densities, safety factor and radial electric field were used to set the initial equilibrium. Zonal flows generated by the fluctuations themselves are self-consistently included and the equilibrium gradients are free to evolve in space and time. Shown in Fig. 3 is a comparison of experimental Δr from an L–mode plasma to two UCAN simulations of the same plasma, one simulation with and one without zonal flows. As can be seen the simulation values of Δr without zonal flows are very long, spanning much of the 65 cm minor radius. With zonal flows included the simulation Δr decrease to near the measured values in both magnitude and radial behavior. In high performance quiescent double barrier (QDB) [9] discharges both experimental measurements and gyro-kinetic UCAN simulations (Fig. 4) indicate a significant reduction in the radial correlation length, as compared to L–mode, consistent with the observed reduced transport. While QDB discharges are known to have weakly reversed central magnetic shear, the effect of this shear was found to be small in the UCAN simulation and so does not explain the simulation Δr. Large zonal flows were produced in the simulation, as much as 20 km/s compared to the experimental measurements of steady state flows of 30 km/s with resulting simulation sheared flows equal to or greater than experiment. The reduced simulation Δr values were consistent with these large zonal flows and attendant E×B velocity shear decorrelation, however no definitive answer has been attained. Research on this is continuing.

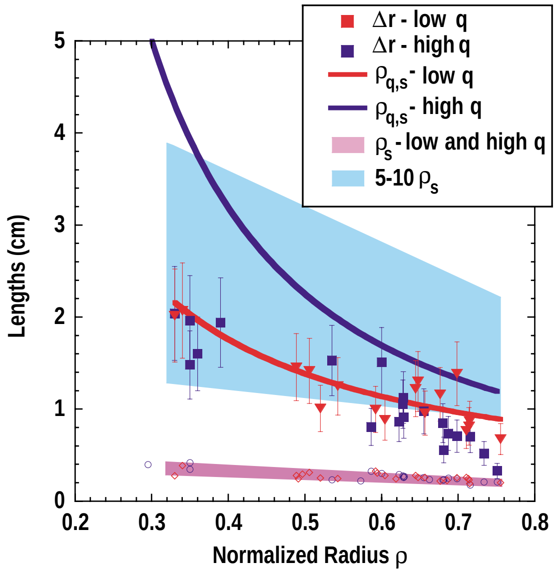

Fig. 2. Experimental radial correlation lengths and various gyro-radii from B_θ scan (at constant I_p) experiment showing little dependence of Δr on B_θ. All are L–mode plasmas.

In addition to these UCAN comparisons, work has begun on comparing to the GYRO code, which is a fully shaped, non-linear simulation, with kinetic electrons, rotation, shaping, Shafranov shift, profile variation, and $\beta > 0$ [4]. In Fig. 5 is shown a preliminary comparison between experimental Δr and results from the GYRO code. The experimental data are taken from a non-dimensional ρ* scaling experiment where ρ* was varied by approximately 1.6 while keeping other parameters (i.e. β, ν*, q, T_e/T_i, Mach number) approximately constant [8]. This experiment was performed by varying the magnetic field between 1 and 2 T while keeping the other parameters (β, q, etc.) constant via adjustment of plasma current, neutral beam injection, and gas puffing. Experimental Δr data from 1 and 2 T for BES and 2 T for reflectometry are shown. Although from different radial locations, the 2 T data from BES and reflectometry are seen to be consistent with each other. The GYRO predictions for 1 and 2 T are consistent with a ρ* type scaling, that is, the ratio $\Delta r_{2T}/\Delta r_{1T}$ is approximately the same as the ratio ρ^*_{2T}/ρ^*_{1T} [10]. The magnitude of both the 1 and 2 T correlation lengths from GYRO are seen to fall within the error bars for the experimental measurement. This rough agreement between experiment and a simulation code incorporating much of the important physics is encouraging. It should be noted that both experimental and simulation values have enough radial variation and uncertainty that basing broad conclusions on single radial points can be misleading. It is much more preferable to have large radial ranges of both experimental and simulation data to compare. An expanded radial range of simulation using GYRO is underway.

Experimental turbulence and transport measurements from L–mode plasmas have also been compared to a gyro-fluid simulation, GRYFFIN [11]. GRYFFIN is a nonlinear gyro-Landau fluid code that computes turbulence in a flux tube centered at a given radius. The transport of

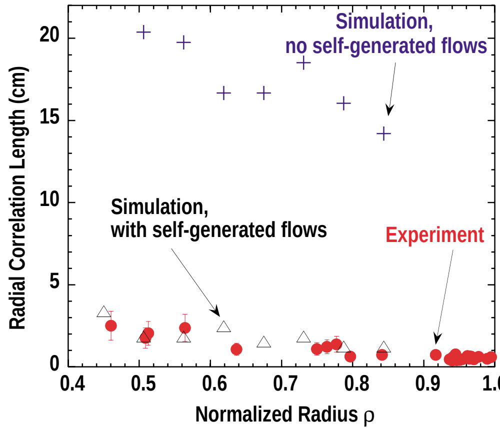

Fig. 3. Radial correlation lengths from experiment (circles) and UCAN simulations with zonal flow (triangles) and without zonal flow (crosses) demonstrating effect of zonal flows on result. L–mode plasma.

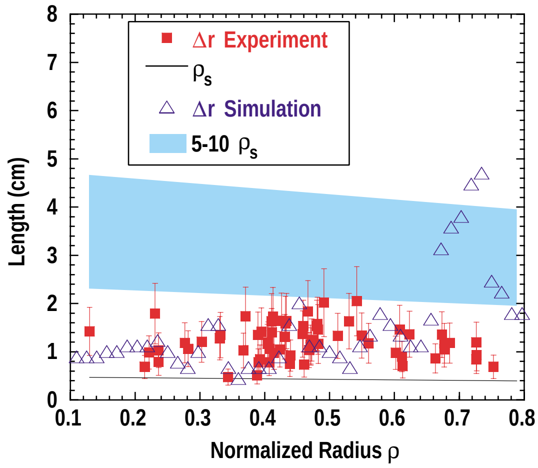

Fig. 4. Experimental and UCAN simulation of radial correlation lengths for quiescent double barrier discharge (QDB). Also shown are ρ_s and 5–10 ρ_s.

both energy and particles is calculated, and trapped electron modes and impurity drift waves are included along with ITG modes. The shape of the simulated poloidal wave number spectrum (from beam emission spectroscopy) is found to be similar to the experimentally measured one with both peaking near $k_\theta\ \rho_s$ ~ 0.32–0.35 [11]. Shown in Fig. 5 are radial correlation lengths from GRYFFIN simulations of the 1 and 2 T plasmas discussed in the previous paragraph. The ratio of correlation lengths $\Delta r_{2T}/\Delta r_{1T}$ taken at r/a=0.7 is approximately the ratio of ρ^*_{2T}/ρ^*_{1T} which is similar to the GYRO results. Additionally, the magnitude of simulation values is near the experimental values, although the radial variation of the GRYFFIN 2 T Δr appears to be less than that of the experiment. Again more radial points in both simulation and experiment would be very useful. The GRYFFIN simulated ion thermal transport is found to be larger than the experimental value by a factor of 1.5 to 2.0, e.g. the total ion thermal flux $Q_{ion,\ experimental}$ ≈ 1.5 MW, while $Q_{ion,\ GRYFFIN}$ ≈ 2.2–3.0 MW [11]. The simulation also overestimates the density fluctuation level by a factor of ~ 4 with $(\tilde{n}/n)_{experiment}$ ≈ 0.4% and $(\tilde{n}/n)_{GRYFFIN}$ ≈ 1.6–1.9%. These differences may be due to profile measurement uncertainties (which affect drive and damping in the simulation), possible underestimates of the effect of E×B shear on the turbulence and transport, as well as zonal flow effects. The GS2 gyro-kinetic code, which includes full shaping, finite beta, and kinetic electrons, is being utilized to further investigate the effect of zonal flows but results so far do not explain the differences based upon this effect alone [12]. The GRYFFIN simulation also underestimates the electron thermal transport; however, this may be due to high wavenumber modes that are not in the simulation and also are not accessible by the available measurements. The existence and importance of high-k effects await new diagnostic measurements and experiments.

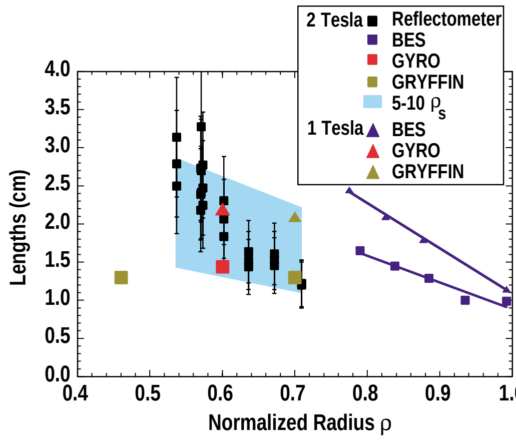

Fig. 5. Comparison of experimental and simulated correlation lengths from GYRO and GRYFFIN codes. L–mode plasma.

3. Summary and Conclusions

The radial correlation length of the turbulence appears to be a quantity that is predicted by the non-linear codes, both gyro-kinetic and gyro-fluid, within a factor of two or so. The ability of the simulations to compute this quantity in near agreement with experiment is likely due to successful modeling of the non-linear processes as well as inclusion of the most important linear drive and damping mechanisms. The inclusion of zonal flow physics is important to this similarity as well as to the overall reduction of transport in the simulations to near experimental levels. Additionally and as mentioned in Section 2, measurements of correlation lengths and times, spectral shapes, etc. are not strongly dependent upon calibrations of the particular instrument, with the absolute level often either normalized out or not affecting the result. Thus some experimental uncertainties can be much reduced in these types of measurements. Conversely, the experimental determination of transport has many sources of uncertainty including beam deposition, fast particle diffusion, MHD transport effects, toroidal asymmetries, etc. as well as basic uncertainties in individual measurements. Due to the variations of both experimental and simulated measurements, radial profiles of quantities to be compared should cover as large a radial range as feasible. The differences observed when comparing experimental and simulated power fluxes and fluctuation levels may be due to a combination of these experimental uncertainties as well as subtleties in linear drives, MHD-related transport, etc. Thus comparisons between experimental and simulation fluxes are perhaps better attained at this point by examination of trends or scalings with relevant plasma parameters such as ρ^* [8, 10, 13], I_P [7], B, etc. Such scalings give clues to whether the underlying physics has been successfully captured within the simulations and also allow testing of specific simulation predictions.

The goal of improved understanding of plasma turbulence and confinement as well as validated predictive capabilities is being advanced by detailed comparisons such as those presented here. New experimental diagnostics as well as expanded comparison efforts will contribute to this goal.

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