COMPARISONS OF MEASUREMENTS AND GYROFLUID SIMULATIONS OF TURBULENCE IN DIII-D

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1. Introduction

In this work, we measure turbulent density fluctuations on the DIII-D tokamak using beam-emission spectroscopy (BES) and compare the results with gyrofluid simulations using the PPPL/IFS code [1]. This code, which has been run extensively to derive transport simulation models [2], now includes trapped electron dynamics and detailed spectral information. Our objective is to examine in greater detail the underlying physics of the turbulent transport.

2. Experimental results

The fluctuation data presented here was taken during the early phase of quiescent inner-wall-limited L-mode plasmas with modulated electron-cyclotron heating (ECH). The discharge parameters were carefully chosen to avoid sawteeth, MHD activity, and ELMs, so as not to confuse interpretation of the results of the ECH modulation. The ECH modulation was approximately square wave with a 40-ms period and 50% duty cycle.

The toroidal field and ECH antenna orientation for the specific discharge discussed here was chosen for localized second-harmonic X-mode heating at 110 GHz at a flux-surface radius of $r/a \approx 0.7$. It should be noted, however, that ~20% of the power was in the O mode, having poor first-pass absorption, and could have been absorbed anywhere along the resonance, most probably inside the flux-surface radius of the X-mode resonance.

The BES system is composed of 32 sightlines separated by ~1 cm in the plasma. These are distributed in a radial array of 20 channels along the plasma midplane and two poloidal arrays of seven channels each (two channels serve in both radial and poloidal arrays) extending below the midplane and separated by 10.7 cm. This pattern, which can be scanned radially, was located such that the poloidal arrays, at R = 2.09 m and 2.20 m (r/a = 0.56 and 0.80), straddled the ECH-resonant flux surface. Since the BES system actually measures Balmer-α emission from the neutral beams, the normalized intensity fluctuations ($\tilde{I}/I$) must be multiplied by a factor of ~2.2 for the plasma conditions of DIII-D to obtain the relative density fluctuations ($\tilde{n}/n$) [3]. Further details of the BES system are described elsewhere [4].

Because of the very low emission fluctuation levels in the interior plasma of DIII-D

(<1%) and the limitation on detectability posed by photon and detector/amplifier noise, a total time window much longer than the period of the ECH modulation is needed for reasonable statistics. Therefore, the measurements in this work (plasma profiles as well as fluctuations) are averaged over ten modulation periods (400 ms of the discharge and 400,000 BES samples at 1 MHz digitization). Modulations of the turbulence by the ECH will be investigated in future work.

To further enhance the statistics, the fluctuation levels are derived from the *cross powers* between adjacent poloidal channels, since electronics and photon noise decorrelate between channels. The cross-power spectra peak at $f_0 \approx 200$ kHz at the inner array and at ~110 kHz at the outer array and are broad (FWHM $\approx f_0$) above ~70 kHz. The fluctuation levels are obtained from the square roots of the cross powers integrated between 70 and 350 kHz. Further corrections for finite sample volumes and correlation lengths [6] yield density fluctuation levels of (0.67 ± 0.06) % and (2.85 ± 0.5) % at the inner and outer arrays, respectively.

The poloidal phase velocity at each array is computed from a pair of channels in each array using time-delay correlations (in agreement with frequency-domain phase shifts). The time-average poloidal phase velocities at the inner and outer arrays, also corrected for finite sample volumes, are 11.3 ± 0.8 km/s and 6.7 ± 0.75 km/s, respectively. The poloidal **E**×**B** velocities, estimated from charge-exchange recombination spectroscopy [5] are 9.9 ± 0.8 km/s and 8.8 ± 0.5 km/sec, respectively. Therefore, the phase velocities in the plasma frame with $E_r = 0$ are 1.4 ± 1.1 km/s (in the ion diamagnetic direction) and -2.05 ± 0.9 km/s (in the electron diamagnetic direction), respectively.

These results are summarized in Table I. Also tabulated is the normalized mean poloidal wave number $k_\theta \rho_i$, obtained from the cross-phase spectrum evaluated at f_0 and corrected for finite sample volumes.

3. Gyrofluid simulations

We have carried out linear and nonlinear gyrofluid flux-tube simulations [1] with plasma parameters corresponding to the locations of the inner and outer poloidal arrays. We employ realistic geometry, obtained from EFIT [7] equilibrium reconstructions. Two ion species (deuterium and carbon) and trapped electrons are included, so that both ion temperature-gradient (ITG) and trapped-electron (TE) modes can be present with impurity effects. Linear calculations serve to identify the dominant modes and their frequencies and growth rates as functions of poloidal wave number k_θ, while nonlinear runs determine the mode saturation levels, wave-number spectra, and transport fluxes (expressed as particle and thermal diffusivities).

Currently not included is the effect of the background **E**×**B** flow shear, which is significant in these discharges which are rotating at nearly 150 km/sec in the toroidal direction at the magnetic axis. Thus, the code overestimates growth rates, fluctuation amplitudes, and fluxes. We will later discuss estimates of the $\omega_{E\times B}$ corrections [8,9] to these.

The nonlinear runs saturate in about 100 drift times, L_n/v_{ti}, corresponding to ~0.3 ms. The turbulence should therefore respond almost instantaneously to profile changes induced by the modulated ECH. Measurements of n_e, T_e, and T_i of sufficient sensitivity were not available, however, to monitor these changes. Therefore, as in the experimental section, our approach is to begin with baseline studies using the time-average profiles.

3.1. Results at the inner poloidal array

At r/a = 0.56, the simulated turbulence is dominated by ITG modes, i.e., modes propagating in the ion diamagnetic direction in the plasma frame. The growth rate is positive for $0 \le k_\theta \rho_i \le 1$, peaking at $k_\theta \rho_i = 0.6$ with a value of $\gamma_{max} = 7.0 \times 10^4$ sec^{-1}, about the same as the real frequency. Trapped electron dissipation accounts for about half of the growth rate. The poloidal phase velocity is $\omega/k_\theta \approx 0.4 v_i^* \approx 0.4$ km/sec, where v_i^* is the ion diamagnetic velocity. Nonlinear calculations yield a k_θ spectrum peaking somewhat lower at $k_\theta \rho_i = 0.45$, and $\chi_i^{eff} = 25$ m^2/sec, $\chi_e^{eff} = 8.1$ m^2/sec, based on the total energy flux $Q_j = \chi_j^{eff} n_j dT_j/dr$. $Q_i^{sim}/Q_i^{pb} = 3.5$, where Q_i^{pb} is derived from a power balance analysis of a similar discharge. Similarly, $Q_e^{sim}/Q_e^{pb} = 2.0$. A significant part of the discrepancy comes from the convective part of the transport, $(5/2)T_j\Gamma_j$, where $\Gamma_j = -D_j dn_j/dr$ is the particle flux, since $\Gamma_i^{sim}/\Gamma_i^{pb} = 27$ and $\Gamma_e^{sim}/\Gamma_e^{pb} = 6.8$. We also find that the density fluctuation amplitude in the simulation is 4% at the outer midplane for these ballooning-like modes.

The estimated shear-flow damping rate $\omega_{E\times B} \approx (5.5 \pm 2.0) \times 10^4$ sec^{-1} (outboard side, less inboard) is sufficient to remove the discrepancy between the measured and simulated energy fluxes. That is, the maximum growth rate, fluxes, and squared fluctuation amplitudes are reduced [9] by roughly the factor $(1 - \omega_{E\times B}/\gamma_{max})$, consistent with the value required to approach marginal stability. Hence, the plasma can easily adjust the gradients (within measurement errors) to achieve the thermal fluxes required by power balance [2], but whether the particle transport can be simultaneously matched needs to be investigated.

3.2. Results at the outer poloidal array

At r/a = 0.8 and $k_\theta \rho_i \le 0.7$, the turbulence is dominated by modes propagating weakly in the electron diamagnetic direction with $\omega/k \approx 0.2 v_i^* \approx 0.2$ km/sec. For larger $k_\theta \rho_i$ the modes propagate weakly in the ion diamagnetic direction. The peak growth rate for all these modes is $\gamma_{max} = 5.9 \times 10^4$ sec^{-1}. At this radius, $\omega_{E\times B} = (2.0 \pm 1.0) \times 10^4$ sec^{-1}, again with large error bars, but again consistent with proximity to marginal stability. In the laboratory frame, the phase velocities are essentially indistinguishable from the **E**×**B** velocity. For this case, the nonlinear runs have so far not yielded consistent results.

The simulation results are also summarized in Table I.

4. Conclusions

These initial comparisons between measurements and gyrofluid simulations of turbulence in

DIII-D have revealed some consistencies and some discrepancies, as evident in Table 1. At the inner array, the poloidal phase velocities of the turbulence, accounting for **E**×**B** convection, are consistent within experimental uncertainties. The simulation result for the mean poloidal wave number is also in rough agreement with the measurements. However, the measured density fluctuation level is considerably less than the simulation value, even accounting for a factor of $\sqrt{2.0}$ to $\sqrt{3.5}$ representing the simulation's overestimate of the fluxes. At the outer array, the only comparison that presently can be made is of the poloidal phase velocities, in which the experimental results seem to indicate stronger propagation in the electron diamagnetic direction than is predicted by the linear simulations. However, the uncertainties in both the experiment and simulations render this conclusion preliminary at best.

Future work involves incorporating **E**×**B** flow shear into the gyrofluid code and repeating the analysis, then examining sensitivity of the simulations to small variations of the profiles. The ultimate goal is to compare measurements and simulations of the time-dependent turbulence during modulated ECH.

R (m)	2.09		2.20	
	Exp.	Sim.	Exp.	Sim.
$\tilde{n}/n$ (%)	0.67 ± 0.06	4.0	2.85 ± 0.5	-
$k_\theta \rho_i$	0.41 ± 0.02	0.45	0.40 ± 0.04	-
$v_{ph,\theta}$ (km/s)	1.4 ± 1.1	0.4	-2.05 ± 0.9	-0.1

Table 1. Measured and simulated turbulence parameters at the locations of the inner (R = 2.09 m) and the outer (R = 2.20 m) poloidal arrays. $v_{ph,\theta}$ is in the plasma frame.

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