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TURBULENCE BEHAVIOR AND TRANSPORT RESPONSE APPROACHING BURNING PLASMA RELEVANT PARAMETERS

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Turbulence Behavior and Transport Response Approaching Burning Plasma Relevant Parameters

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Multi-scale turbulence properties are significantly altered and typically exhibit increased amplitude in high-beta inductive plasmas as parameters approach those anticipated in burning plasmas, such as low rotation and $T_e/T_i \sim 1$ (Fig. 1.) These increases, observed with multiple fluctuation diagnostics in high performance H-mode plasmas on DIII-D, explain the consequent local transport and global energy time confinement response. Burning plasma conditions differ from those typically achieved in beam-heated high performance plasmas in several important ways: equilibrated ion and electron temperatures, low average injected torque and toroidal rotation, as well as low ρ*, low ν* and low q_{95}. Broadband fluctuation amplitude and correlation characteristics are affected by these conditions, as is transport in all channels. Increased fluctuation amplitudes are observed as a result of reducing core toroidal rotation (and consequent ExB shear) and increasing T_e/T_i. Density and temperature fluctuation measurements were obtained over a broad wavenumber and radial range, and provide a basis for quantitative comparisons with nonlinear simulations to test turbulent transport models and to validate simulations near burning plasma conditions.

The energy confinement time is reduced by about 40% as the toroidal rotation is decreased by nearly a factor of three, while core turbulence increases in matched advanced-inductive plasmas ($\beta \approx 2.7$, $q_{95}=5.1$). Toroidal rotation was controlled in these experiments via co-current and counter-current neutral beam injection, and the maximum core Mach number, M ($=V_{TOR}/V_{TH,I}$), approached M=0.5. Density, electron and ion temperature profiles, as well as relevant dimensionless parameters (β, ρ*, q_{95}, T_e/T_i, and ν*) were maintained nearly fixed as toroidal rotation was varied, Ω_{TOR} shown in Fig. 2. Further reduction in toroidal rotation led to the onset of m/n=2/1 neoclassical tearing modes, which were avoided for this comprehensive transport analysis.

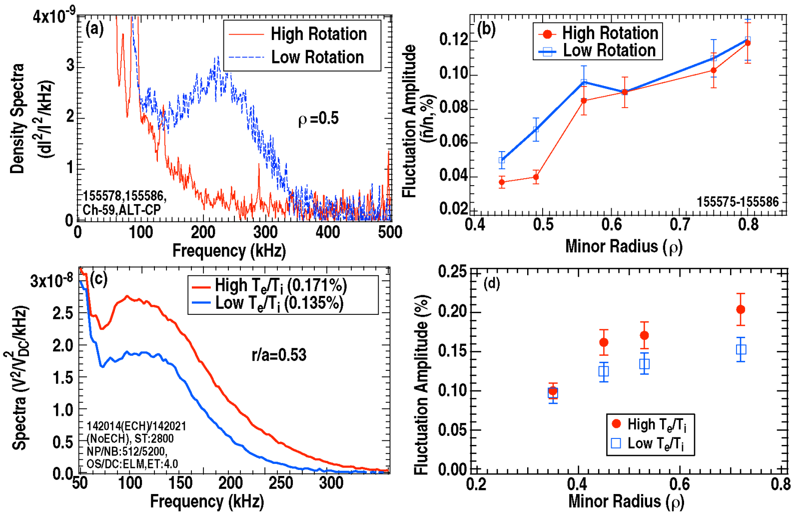

Fig. 1. Comparison of density fluctuation measured with BES vs rotation: (a) spectra near ρ=0.5 (b) low-k fluctuation amplitude profile, and vs T_e/T_i: (c) spectra near ρ=0.5, and (d) fluctuation amplitude profile.

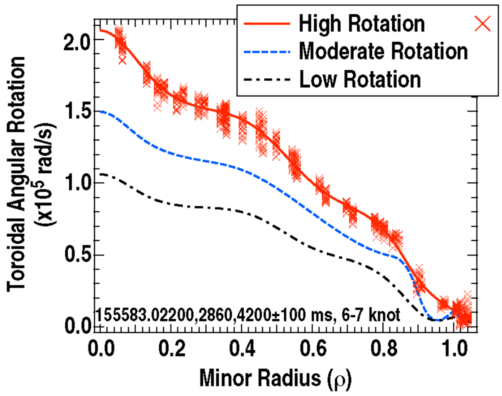

Fig. 2. Carbon rotation profile during injected torque/rotation scan.

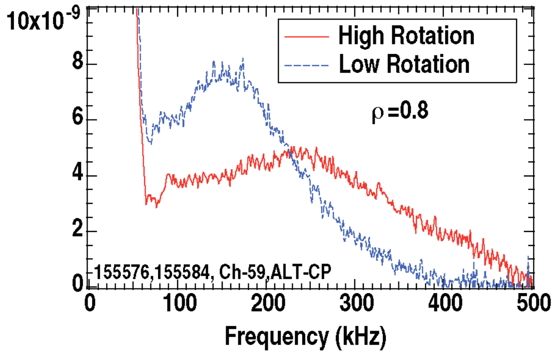

Fig. 3. Comparison of density fluctuation spectra from BES at high and low rotation (integrated amplitudes, ñ/n, are nearly identical)

ExB shear profiles changed significantly with rotation, with a profile-averaged reduction in shearing rate at lower rotation. Core density fluctuations over the range $0.5<k_{\perp}<10$ cm^{-1}, measured with beam emission spectroscopy (BES), Doppler backscattering system (DBS) and phase contrast imaging (PCI), show a reduction in frequency range (corresponding to reduced Doppler shift) and increasing amplitude with reduced rotation, consistent with a rise in transport. Low-wavenumber ($k_{\perp}\rho_i<1$) density fluctuations near mid-radius show significant amplitude reduction, shown in Fig. 1(a), along with a slight reduction in radial correlation length at high rotation, while fluctuations in the outer region of the plasma, $\rho>0.6$, (Fig. 3) exhibit little change in amplitude [Fig. 1(b)].

In related experiments, low-k density fluctuations are observed to increase over the radial range $0.3<\rho<0.8$ [Fig. 1(c,d)] as the T_e/T_i ratio is raised towards unity. The electron to ion temperature ratio was systematically increased by 25% via application of 3.5 MW of off-axis electron cyclotron heating, while core ion temperature and rotation were held nearly constant via feedback control. The T_e profile is uniformly increased, to maintain similar electron temperature gradient scale length. In addition, the spatial correlation properties are modified, suggesting a change in the dominant underlying instability driving the observed turbulence, perhaps reflecting a changing balance of ITG and TEM turbulence. Commensurate with this fluctuation amplitude increase with T_e/T_i, transport increases in all channels (χ_i, χ_e, χ_φ, D), with χ_i compared in Fig. 4, while energy confinement time is reduced by 30%. Initial TGLF modeling shows significant changes to linear growth rates and saturated turbulence levels as T_e/T_i is increased.

These results establish the turbulence mechanisms, including increases in amplitude and changes in wavenumber structure and correlation properties, behind transport modifications approaching burning plasma-relevant conditions; these point towards reduced energy confinement that may require transport reduction techniques to optimize performance. Validating simulations via comparison to these measurements will be crucial to accurately predicting confinement in burning plasmas.

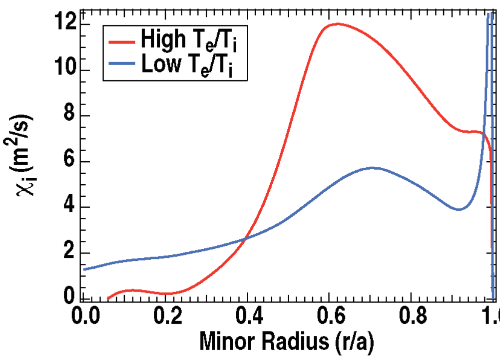

Fig. 4. Ion thermal conductivity at high and low T_e/T_i.

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