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CONTROLLING H-MODE PARTICLE TRANSPORT WITH MODULATED ELECTRON HEATING IN DIII-D AND ALCATOR C-MOD VIA TEM TURBULENCE

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Controlling H-Mode Particle Transport with Modulated Electron Heating in DIII-D and Alcator C-Mod via TEM Turbulence EX-C

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This work develops a quantitative understanding of the mechanisms for increased particle transport with electron heating in (quiescent) H-mode plasmas. We present DIII-D experiments, conducted during the first DIII-D National Fusion Science Campaign, which demonstrate that H-mode core particle transport and density peaking can be locally controlled by modulated electron cyclotron heating (ECH) [Fig. 1(a,b)]. Gyrokinetic simulations show density gradient-driven trapped electron modes (TEM) are the only unstable drift modes in the inner half-radius, where the density profile responds to local ECH. Particle and thermal

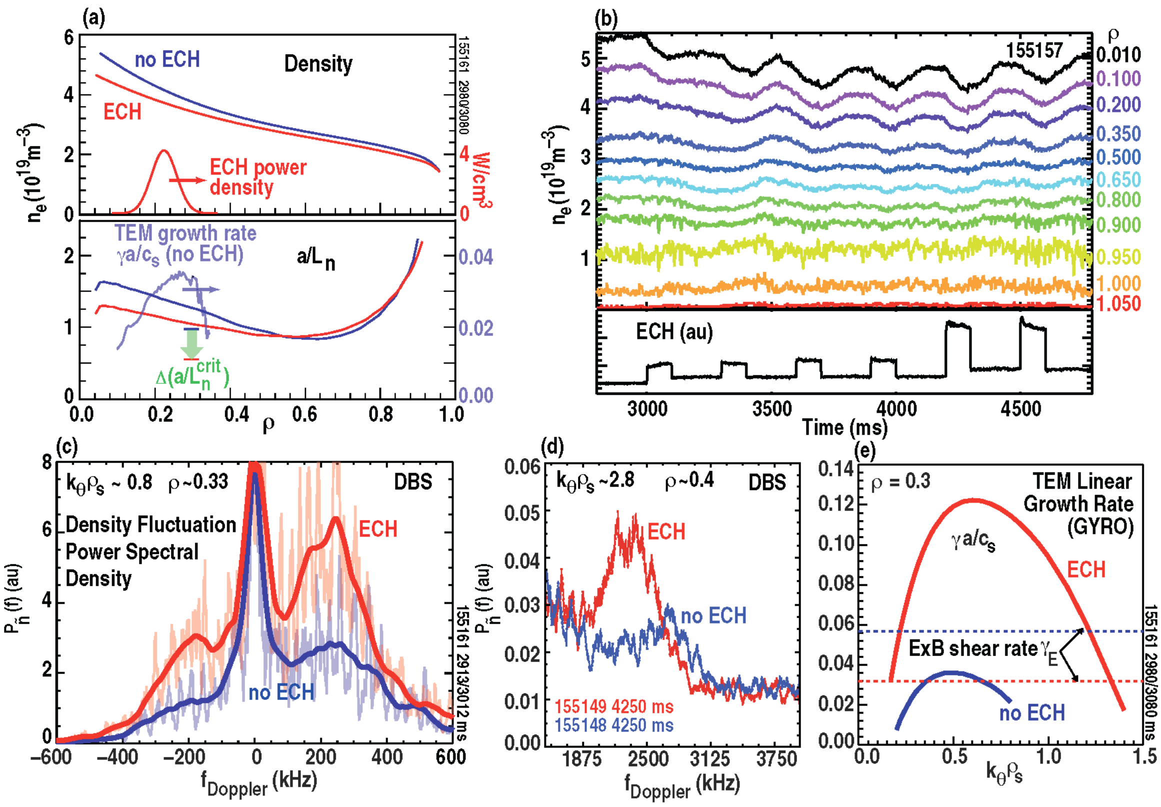

Fig. 1. (a) Response of DIII-D QH-mode density profile to ECH: a/L_n is reduced by ECH where TEM is sole instability, while TEM critical density gradient a/L_n^{crit} is reduced by T_e/T_i, (b) density response to modulated ECH is localized to inner half-radius, (c) DBS core density fluctuation intensity increases strongly during ECH at TEM wavenumbers $k_\theta\rho_s$~0.8 at the radius of TEM, (d) pronounced core density fluctuation feature at $k_\theta\rho_s$~2.8 seen with ECH, and (e) reduced a/L_n^{crit} quadruples the TEM growth rate during ECH.

energy transport driven by TEMs increases strongly with electron temperature, reducing the density gradient during ECH. Thus α-heating could reduce density peaking, providing a feedback loop for the self-regulation of fusion power. The DIII-D experiments complement Alcator C-Mod experiments which controlled H-Mode core particle transport with modulated minority ICRF heating [1,2]. In DIII-D, density profiles were obtained with high-resolution profile reflectometry, augmented by a suite of local fluctuation measurements. A consistent picture emerges from both studies, in which density gradient driven TEM turbulence is strongly driven by the increased electron temperature in conjunction with density peaking. A pronounced increase in core density fluctuations in the TEM range of wavelengths ($k_\theta \rho_s$~ 0.2–2) is observed during electron heating in both C-Mod and DIII-D [Fig. 1(c,d)].

Extensive gyrokinetic simulations of the experiments, including several thousand linear and several hundred GS2 nonlinear TEM simulations for Alcator C-Mod, reproduce measured phase contrast imaging density fluctuation levels using a new synthetic diagnostic, while matching the energy transport inferred from TRANSP analysis. A new nonlinear upshift in the TEM critical density gradient, associated with zonal flow dominated states, increases strongly with collisionality [1,2]. In the C-Mod experiments, the density gradient is clamped by the nonlinear TEM critical density gradient at nearly twice the linear threshold in a new limit-cycle stability diagram [1], in close quantitative agreement with simulations. The DIII-D experiments, an order of magnitude lower in collisionality than C-Mod, test the predicted collisionality variation of the TEM nonlinear upshift while allowing T_e/T_i to vary. Central densities of 9×10^{19} m^{-3} were obtained in DIII-D with low torque and gas fueling.

As shown in Fig. 1(a,b), the density responds locally to ECH. The TEM driving factor, a/L_n=-d(ln n)/dρ, is reduced by ECH where the TEM dominates, with growth rate profile shown in Fig. 1(a) (before ECH). The increased T_e/T_i due to ECH halves the critical density gradient from GYRO, quadrupling the TEM growth rate [Fig. 1(e)]. Density fluctuations from Doppler backscattering (DBS) increase markedly in the inner core during ECH, at TEM wavenumbers $k_\theta\rho_s$~0.8 in Fig. 1(c), while a pronounced core feature appears at $k_\theta\rho_s$~2.8 [Fig. 1(d)]. Measurements near ρ~0.33 show that during ECH, intermittent quasi-coherent fluctuations at TEM wavelengths strengthen, while associated broadband turbulence intensifies and Doppler broadening is reduced (Fig. 2). The quasi-coherent modes appear to have adjacent high toroidal mode numbers n~28, separated in frequency by the Doppler shift; the GYRO TEM phase velocity varies only weakly with n. High resolution gyrokinetic simulations will be closely compared with these measurements. Density fluctuation levels from beam emission spectroscopy near ρ~0.7 also strongly increase during ECH. Core carbon density and metallic line intensities were strongly modulated by ECH, consistent with TEM expectations. Finally, profile stiffness tests were performed via gas puff modulation that varied a/L_n as well as collisionality.

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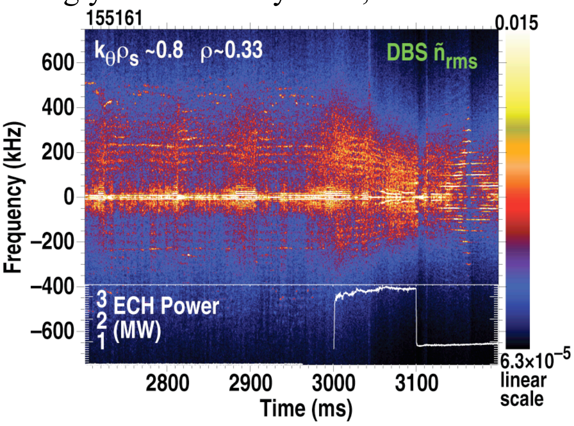

Fig. 2. Frequency spectrum of inner core density fluctuations from DBS reveals high frequency quasi-coherent modes, with stronger broadband turbulence at TEM wave-numbers during ECH. Toroidal rotation slows during ECH, reducing Doppler broadening.