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Bifurcation of Magnetic Islands to a High Temperature State due to Electron Cyclotron Heating in DIII-D

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New observations and analysis of magnetic island evolution with ECCD in DIII-D provide first evidence supporting the recent theory of current condensation [1]. This is important as magnetic islands are the primary cause of tokamak disruptions and ECCD condensation offers potential to stabilize larger islands with given gyrotron power. Condensation gives rise to exponential dependence of the ECCD efficiency on the local T_e. Nested flux surface topology and reduced cross-field diffusivity ($\chi_\perp$) produce good confinement at the island O-point [2] which enables electron temperature peaking (ΔT_e) due to ECCD [3]. If the condensation occurs in an island, subsequent stabilization leads to a hysteresis in the heat source (P_o) and $\Delta T_e/T_e$ parameter space, offering an opportunity to test the theory in experiments. $P_o = PW^2/(\chi_\perp n_e)$), where P is the ECH power density within the island, W is the island width, n_e is the electron density.

For the first time, we report empirical observations of magnetic island bifurcation to a high ΔT_e state due to ECCD. Subsequent stabilization leads to a hysteresis in the (P_o, $\Delta T_e/T_e$) parameter space in qualitative agreement with [1]. We studied H-mode discharges with 2/1 islands of 9 cm width at ρ=0.47, rotating at 9 kHz [Fig. 1. (a)]. The plasma had 1.76 (0.56) m major (minor) radius, 0.93 MA plasma current, 1.9 T toroidal field, zero loop voltage, 11.7 MW neutral beam, 3 MW ECH and 60 kA ECCD.

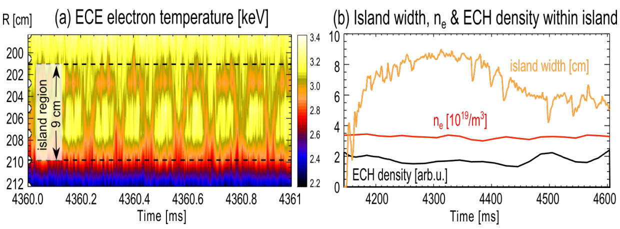

Fig.1. (a) Te contour, (b) W, ne and ECH power density.

P, W and n_e are shown in Fig.1. (b). P is calculated via ray tracing, W is obtained from n=1 Mirnov data and local T_e [4] and constant $\chi_\perp$ is assumed [2]. T_e is obtained via the electron cyclotron emission (ECE) radiometer with 500 kHz sampling rate 0.3 cm above the low field side tokamak mid-plane. The island rotation enables probing T_e with respect to the helical phase (ξ = mθ-nϕ, where θ and ϕ are the poloidal and toroidal angles). T_e is transformed from the lab frame to the island frame via phase-locking ($T_e(R; t) \rightarrow T_e(R; \xi, t)$) [2] [Fig.2. (c,d)]. ΔT_e is calculated from $T_e(R; \xi, t)$.

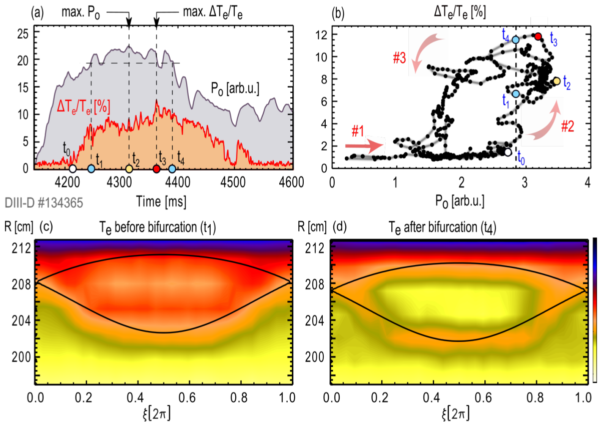

Fig. 2. Po(t) and $\Delta T_e(t)/T_e(t)$, (b) $P_o(t)$ vs $\Delta T_e(t)/T_e(t)$, (c/d) ΔT_e before/after bifurcation at the same P_o.

The time histories of $\Delta T_e/T_e$ and P_o are shown in Fig. 2. (a) while $\Delta T_e/T_e$ is shown with respect to P_o in Fig. 2. (b). The evolution of P_o is dominated by the tearing growth as n_e and P are nearly constant. Once ΔT_e forms (t_0), it continues to grow as P_o dictates. This is expected from the linear diffusion equation. As ΔT_e grows, the island growth gradually slows until at a sufficiently large ΔT_e the island begins to shrink (t_2). This is consistent with direct stabilization caused by the ECCD. After the island starts shrinking, ΔT_e is expected to shrink as well by linear theory. However here ΔT_e continues to grow by about 50% (until t_3). This behavior is not explained by the linear diffusion equation. As the island continues to shrink, $\Delta T_e/T_e$ eventually begins to shrink on a slower rate than in the island growth phase (after t_3). This results in a hysteresis in the ($\Delta T_e/T_e$,P_o) parameter space [Fig. 2. (d)]. This non-linear evolution with two distinct solution branches clearly shows that a bifurcation must have occurred. Thermal energy maps before and after the maximum of P_o (at t_1 and t_4), at the same P_o are shown in Fig. 2 (c) and (d) respectively. $\Delta T_e/T_e$ increases from 8% to 11% between these time points.

These observations are important as the spontaneous bifurcation to higher $\Delta T_e/T_e$ may enable the stabilization of larger islands. In this experiment, the island growth is stabilized only after the bifurcation occurs. Therefore, this phenomenon may be crucial for avoiding disruptions caused by tearing modes in tokamaks.

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