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Facilitation of NTM control via ECCD due to current condensation effect in RMS tokamak plasmas

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Achieving self-sustained burning in ITER and future large-scale fusion devices requires good confinement. These devices will operate at low collisionality and high pressure, generating substantial bootstrap current. However, this large bootstrap current poses a threat by driving neoclassical tearing modes (NTMs). To mitigate or actively control NTMs and avoid disruptions, electron cyclotron current drive (ECCD) has been developed. Although ECCD has proven effective for stabilizing NTMs in both experiments and simulations, controlling off-normal events that trigger extremely large islands remains challenging for future large-scale devices like ITER.

Recently, Reiman et al. identified a radio frequency current condensation effect that nonlinearly enhances ECCD stabilization efficiency, enabling effective control of extremely large islands. This effect, reported in [1], is modeled in the nonlinear resistive MHD code MHD@Dalian Code [2-4]. A series of numerical studies investigates how current condensation amplifies ECCD during NTM suppression in tokamak plasmas [2]. Nonlinear simulations numerically verify the ECCD input power threshold and fold bifurcation phenomenon, showing good agreement with analytical predictions. When accounting for current condensation, ECCD effectiveness for large NTM islands significantly improves: larger islands stabilize more effectively than smaller ones at a given input power. This challenges the conventional strategy of activating ECCD as early as possible. The underlying physics of ECCD stabilization is discussed in detail. This work presents the first implementation of the current condensation effect within a nonlinear resistive MHD code. Our investigations demonstrate that this effect significantly enhances the effectiveness of ECCD stabilization for larger NTM islands. Crucially, stabilization efficacy increases with island size—indicating that the condensation effect will likely play a critical role in managing off-normal events in future large-scale fusion devices.

Based on the aforementioned investigation, the control of NTMs in a reversed magnetic shear (RMS) configuration in the consideration of current condensation effect is employed. Numerical simulations investigate how the current condensation effect enhances ECCD and controls burst phenomena in RMS configurations (figure 1). Key findings reveal:

For tearing modes (TMs): Current condensation doubles ECCD efficiency, halving required input power in optimal regimes.

For neoclassical tearing modes (NTMs): Stabilization time decreases with island size, challenging early ECCD initiation protocols.

For burst phenomena: The effect suppresses otherwise eruptive large islands, enabling size-dependent current drive activation and wider plasma stability margins (figure 1).

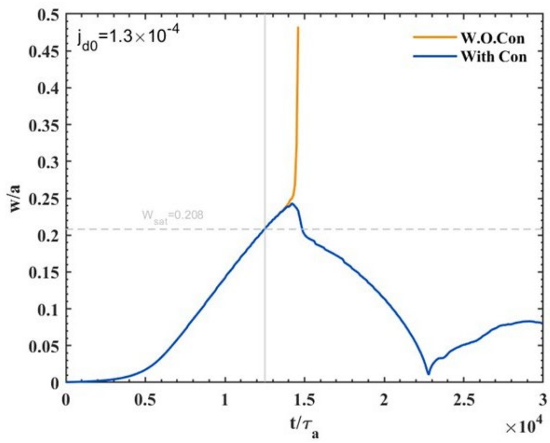

Figure 1. Temporal evolution of magnetic islands in the vicinity of the outer rational surface.

References
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