Nonlinear Diamagnetic Stabilization Effects on $m = 2$, $n = 1$ Cylindrical Double-Tearing Modes in Hall MHD Simulations

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Introduction

Reversed-shear tokamak configurations have some promising features for improved stability and confinement that may be able to Double-Tearing Modes (DTMs). Nonlinearly these instabilities can potentially cause significant plasma motion and disruptions of the similar current ring [2, 3]. Recent research has shown that equilibrium shear flows can have a stabilizing effect on both linear and nonlinear DTMs. If the rotation between the two tearing surfaces is large enough compared to the growth rate ($\Delta \omega \gg \gamma$) they cannot couple linearly and the system collapses to two localized eigenmodes [6], though they may re-couple nonlinearly. Diamagnetic drifts (characterized by the frequency $\omega_d$) have the potential to provide both differential rotation and additional reconnection-like stabilization [7]. Internal Transport Barriers (ITBs) with significant pressure gradients are frequently observed in reversed-shear configurations [5], suggesting $\omega_d$ effects are likely a candidate for stabilization. We extend our previous work on linear $\omega_d$ stabilization into the nonlinear regime of an $m = 2$, $n = 1$ DTM in cylindrical geometry using the extended MHD code MRC-3D. While we do find evidence of nonlinear stabilization, we find the effectiveness is highly dependent on the location of the pressure profile.

Equilibrium

We use the non-monotonic safety factor profile from Ref [4]

$$\psi(r) = \psi_0 (r/r_0)^{1/2} \exp\left[-\left(r/r_0 - n_0/r_0\right)^2\right] + \psi_{box}(r)$$

$$\nabla \psi \cdot \nabla \psi = \psi_0 \left[1 + \left(r/r_0 - n_0/r_0\right)^2\right]$$

with the constant values $r_a = 0.667$, $\psi_0 = 3.832$, $\omega_d^* = 0.238$, $\omega_d = 0.629$. $r_s0 = 0.394$, $m = 2$, $n = 1$. $\omega_0$ may be varied near 0.2 to change the separation $D$ between two inner-$q$ surfaces. Assuming $R_{in} = R_{out}$ then we find the in-plane $R_{in}$. For this work we fix $\gamma = 2.5$, giving $\Omega \approx 0.76$.

Density profiles are of the form [5]

$$N(r) = N_0 \left(1 - N_1 \tanh(r_0/r) + \tanh(r_1/r)\right)$$

where $N_0 = 1$, $r_s1 \leq r \leq r_s2$, and $r_0(2)$ is the inner (outer) $q$ = 2 surface. The parameters $\delta_1$, $N_1$, and $r_0$ are chosen based on the desired diamagnetic drifts ($\omega_d$) at each tearing surface. Temperature $T = 1$ is uniform.

MRC-3D Model

Setup of Nonlinear Simulations

Based on our previous studies of this system we expect the linear decoupling to be in the range 0.01 < $\Delta \omega < 0.05$. We use these bounds as characteristic ‘coupled’ and ‘decoupled’ states and examine them non-linearly for different locations of the peak pressure gradient. In addition to localizing the drift at the inner and outer rational surfaces, we consider a case with equal drifts at both locations to eliminate differential rotation effects.

The value of $\omega_d$ at the rational surfaces is determined by several different parameters. For this work we fix $\delta_1 = 0.1$. The pressure profiles $r_s0$ and $r_0$ are set as follows for the three configurations of interest.

Equal Drift $\omega_d^* = 0.02$ is fixed. The parameters $N_0$ and $r_0$ are set to achieve the desired drifts: $\omega = 0.05 |N_0| = 0.298, r_0 = 0.641; |\omega(1)| = 0.068, r_0 = 0.378$.

In Inner Drift the pressure gradient is localized around the inner rational surface, with nearly no drift at the outer. The parameters $\delta_1 = 0.1$ and $r_s0 = r_s2$ are fixed. $N_0$ is set to achieve the desired drift: $\omega = 0.05 |N_0| = 0.762$.

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Outer Drift $\omega_d^* = 0.02$ is fixed. The parameters $N_0$ and $r_0$ are set to achieve the desired drifts: $\omega = 0.05 |N_0| = 0.762, r_0 = 0.378$.

References

7. [B. Rogers, L. Zhdanov “Nonlinear $\omega_d$-stabilization of the m = 1 mode in tokamaks” Phys. Plasmas, 2, 3428 (1995)]