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ELECTRON DENSITY WINDOW ON THE SUPPRESSION OF SPONTANEOUS NEOCLASSICAL TEARING MODE WITH HIGH FRACTION OF BOOTSTRAP CURRENT

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Abstract

Plasma major disruptions represent one of the most critical challenges in the pursuit of sustained magnetic confinement fusion. They not only severely limit the steady-state operation of tokamak devices but also pose a tangible risk of damaging key plasma-facing components, potentially leading to substantial economic and operational setbacks. In future fusion reactors, such as those envisioned for DEMO and commercial power plants, operation is anticipated to occur under high-confinement regimes (e.g., H-mode) where a significant fraction of the plasma current is expected to be bootstrap-driven. Under such conditions, the neoclassical tearing mode (NTM) is projected to become a dominant instigator of major disruptions, owing to its propensity to degrade energy confinement and trigger sudden loss of plasma stability. Conventionally, the triggering of NTMs can be mitigated by suppressing the formation of seed magnetic islands, which often originate from other magnetohydrodynamic instabilities or external perturbations. However, a substantial body of experimental evidence has shown that NTMs can also develop spontaneously, even in the absence of detectable seed islands. This spontaneous growth presents a particularly challenging scenario for disruption avoidance strategies, as it implies the existence of an intrinsic triggering mechanism that cannot be entirely eliminated through conventional control approaches. Recently, experiments on the TCV tokamak have revealed a promising pathway for suppressing such spontaneous NTMs. Researchers observed that by systematically varying the electron density, a specific operational window emerges within which the spontaneous mode is completely suppressed. This phenomenon is believed to be closely linked to the electron diamagnetic effect, which is known to play a dual role in influencing mode stability—acting both as a drive and as a stabilizing mechanism depending on the local gradient and drift dynamics. Motivated by this experimental discovery, the purpose of this work is to conduct a systematic numerical investigation into the underlying physical mechanism of this electron density window, particularly under conditions of high bootstrap current fraction. We employ a self-developed, four-field reduced MHD code, which incorporates the electron diamagnetic effect in a fully consistent manner. Through a series of well-designed numerical scans and stability analyses, we aim to clarify the relationship between the NTM triggering threshold and the electron diamagnetic stabilization mechanism, as well as to evaluate the influence of various key plasma parameters—such as the current profile, pressure gradient, and magnetic shear—on the width and location of the stabilizing density window. Ultimately, this study seeks to provide a theoretical foundation for the effective suppression of spontaneously triggered NTMs, thereby contributing to the development of robust disruption avoidance strategies essential for the safe and efficient operation of next-generation fusion experiments and future reactor-scale devices.

1. INTRODUCTION

Plasma major disruptions represent one of the most critical challenges in tokamak operation, posing not only a significant threat to steady-state performance but also carrying the potential to cause severe damage to the device itself. In future fusion reactors, operations are anticipated to occur under high-confinement regimes characterized by a substantial fraction of bootstrap current. Under these conditions, the neoclassical tearing mode (NTM) is expected to emerge as the primary instigator of major disruptions. This mode is particularly dangerous in reactor-scale tokamaks due to its detrimental impact on achievable plasma beta and its direct role in triggering disruptive events. The economic implications of such disruptions—including possible damage to experimental components—underscore the urgent need to develop effective mitigation and active control strategies for NTMs, which have been identified as a high-priority issue for the performance and safety of advanced devices such as ITER and future commercial reactors.

In general, the onset of NTMs can be prevented by eliminating the sources of seed magnetic islands, which often arise from other magnetohydrodynamic (MHD) instabilities or external perturbations. However, in numerous experiments, spontaneous NTMs have been observed to develop even in the absence of clear seed islands, indicating the existence of an alternative triggering mechanism. Recent experiments on TCV (Tokamak à Configuration Variable) have revealed a promising phenomenon: a specific window in electron density where spontaneous NTMs can be completely suppressed [1]. This observation opens a new pathway for avoiding such modes in future fusion devices without relying on external control actuators.

It is therefore essential to understand and exploit this density-dependent suppression mechanism to enable stable, high-performance operation in next-step large-scale devices. The purpose of this work is to numerically investigate the underlying physics of this electron density window under high bootstrap current conditions, using the self-developed three-dimensional (3D) MHD code (MHD@Dalian) [2–7], which incorporates the electron diamagnetic effect. Through systematic simulations, we aim to clarify the relationship between the NTM triggering threshold and the electron diamagnetic stabilization effect, as well as to evaluate how various key plasma parameters—such as pressure gradient, current profile, and magnetic shear—influence the width and location of the density window. The findings are expected to provide theoretical support for the effective suppression of spontaneously triggered NTMs and contribute to disruption avoidance strategies, together with the real time multi-mode 3D MHD spectroscopy [8-10], in future fusion experiments.

2. NUMERICAL MODELLING

The nonlinear evolution of NTMs is numerically investigated using a set of four-field MHD equations that include the two-fluid effect. The nonlinear equations in a cylindrical geometry (r,θ,z) can be written as:

$$\frac{\partial\psi}{\partial t} = [\psi,\varphi] - \partial_z\phi + \beta_e\delta_i\left(\nabla_{//}n + 2\nabla_{//}T_e\right) - S_A^{-1}(j - j_b) + E_{z0}$$
$$\frac{\partial u}{\partial t} = [u,\varphi] + [j,\psi] + \partial_z j + R^{-1}\nabla_\perp^2 u$$
$$\frac{\partial v}{\partial t} = [v,\varphi] - \nabla_{//}(nT_e) + R^{-1}\nabla_\perp^2 v$$
$$\frac{\partial n}{\partial t} = [n,\varphi] + 2\delta_i\nabla_{//}j - \nabla_{//}(nv) + D_\perp\nabla_\perp^2 n + S_{n0}$$

In the model, ψ, φ, v and n represent magnetic flux, stream function, parallel ion velocity and electron density, respectively. The quasi-neutrality condition is assumed in the model. The radial coordinate r is normalized via the plasma minor radius. j_b is bootstrap current density. More details please find in [7].

3. MODELLING OF TCV EXPERIMENTS

In this work, the control of plasma density is numerically implemented by adjusting the ion skin depth, $\delta_i \propto 1/\sqrt{n}$, within the simulation model, while maintaining a fixed normalized density profile. This approach enables a systematic investigation of density effects without altering the shape of the density gradient, which is crucial for isolating the role of diamagnetic stabilization in mode behavior. In the TCV experiments referenced, an on-axis electron cyclotron current drive (ECCD) is employed to non-inductively drive plasma current. As the EC power is raised, it leads to an increase in the total plasma current, which in turn enhances the magnetic shear in the vicinity of the q = 2 rational surface—a key region for the onset of 2/1 neoclassical tearing modes (NTMs).

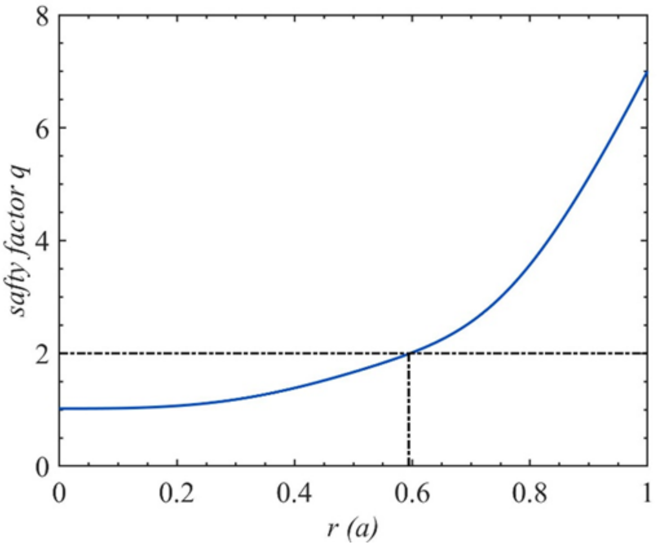

FIG. 1. The initial safety factor profile.

The safety factor q-profile is adopted in the simulation as shown in Fig. 1. To replicate this experimental setup in our MHD@Dalian (MDC) simulations, the local magnetic shear around the 2/1 surface is systematically varied, effectively modeling the influence of increasing ECCD power. Through this approach, the previously reported density window for NTM suppression is successfully reproduced. Furthermore, as illustrated in Fig. 2, this stabilizing density window is shown to expand with increasing EC power, highlighting the synergistic role of magnetic shear and density in controlling mode stability.

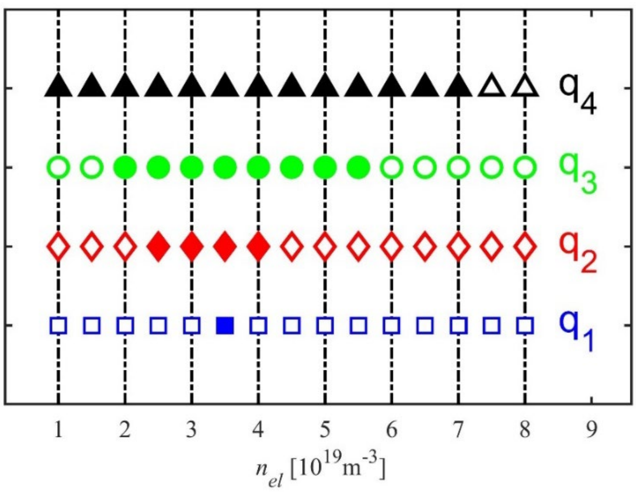

FIG. 2. Electron density window of spontaneously triggering NTM obtained via numerical simulation of MDC.

To interpret this phenomenon theoretically, the modified Rutherford equation is employed. Within this framework, the electron diamagnetic effect can be decomposed into two competing contributions: the density gradient, which acts as a driving term for the mode, and the diamagnetic drift flow, which exerts a stabilizing influence. As the plasma density increases, these two effects alternately dominate, giving rise to a non-monotonic overall impact of the diamagnetic term on mode stability. Under the assumption of a negative classical tearing mode stability index, this dual role naturally leads to the emergence of a density window—a parameter region where the mode is fully suppressed. The schematic paradigm is shown in Fig. 3.

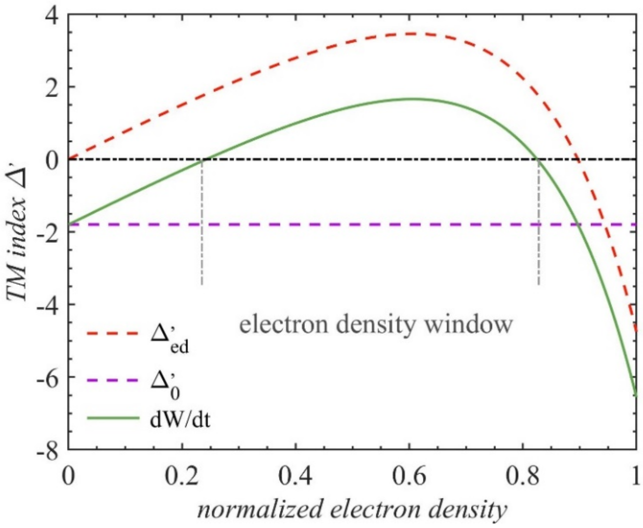

FIG. 3. Schematic paradigm of the physics behind the electron density window.

In parallel, linear MHD simulations using the MDC code are performed to model the experimental scenario of EC power ramping. As shown in Fig. 4, when the magnetic shear near the q = 2 surface exceeds a critical value, a 2/1 NTM is triggered—consistent with the experimental observations from TCV [1]. The simulated mode rotates in the electron diamagnetic drift direction, matching the experimental measurements. The rotation frequency is of the same order of magnitude as that observed in experiments and remains only weakly sensitive to further increases in magnetic shear.

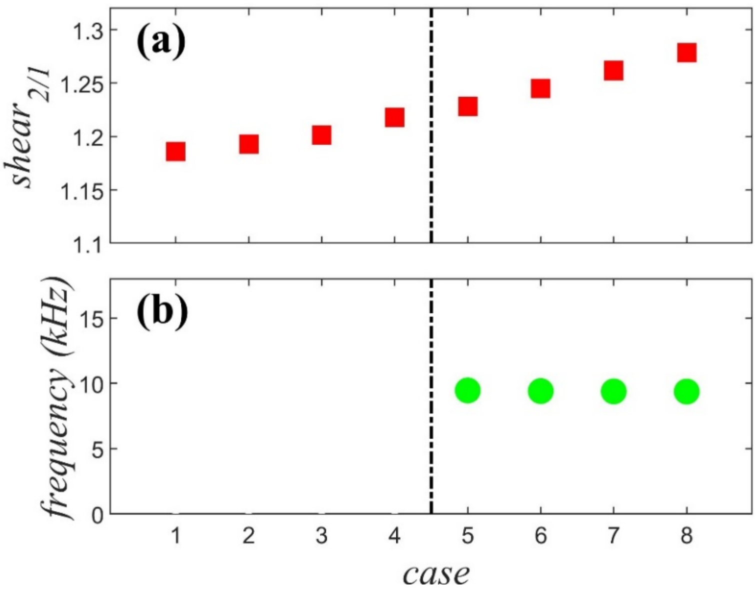

FIG. 4. Modelling of EC power ramp-up experiment via MDC.

Additionally, density ramp-up experiments from TCV are modeled using analogous linear simulations, with results summarized in Fig. 5. Both the rotation frequency and the density threshold for mode suppression are consistent with experimental values. The rotation frequency is found to decrease with increasing density—a trend also captured in the experiments.

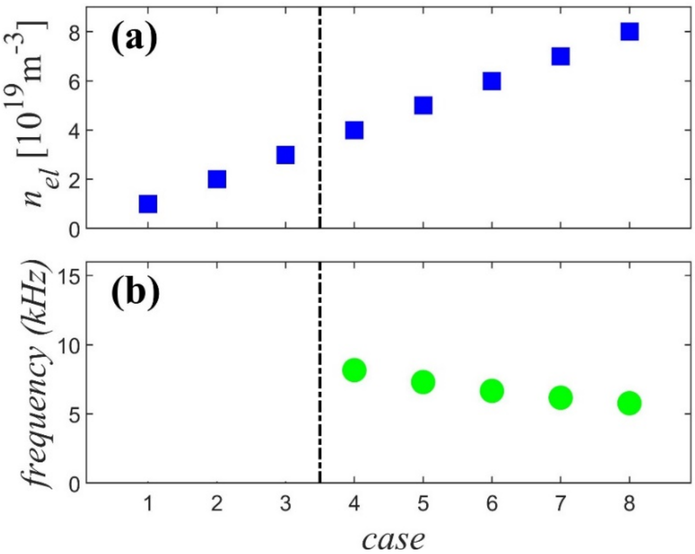

FIG. 5. Modelling of density ramp-up experiment via MDC.

Based on the framework established by linear simulations, we have proceeded to conduct a series of nonlinear simulations to investigate the temporal evolution of both the magnetic island width and the corresponding mode rotation frequency. These simulations were specifically designed to model the two distinct modes observed in the TCV experiments, aiming to elucidate their nature and nonlinear dynamics. The numerical results strongly indicate that the experimentally observed "upper mode" is, in fact, a high-order harmonic of the fundamental 2/1 mode. This identification resolves a key question regarding the mode's identity and provides a new perspective for interpreting its behavior. Both the fundamental 2/1 mode and its high-order harmonic are found to rotate in the electron diamagnetic drift direction, consistent with the experimental measurements. The nonlinear evolution of the mode frequency reveals a complex and multi-stage process. Immediately after the mode onset, the rotation frequency exhibits a sharp, abrupt drop. This initial rapid deceleration is primarily attributed to a strong electromagnetic drag force arising from the interaction between the nascent magnetic island structure and the surrounding background plasma. Following this initial transient phase, a period of relative stability is observed. When the magnetic island remains small in width, its influence on the local plasma profiles is limited. Consequently, the mode rotation frequency enters a flattop phase, maintaining an almost constant value for a significant duration. However, as the island gradually grows to a larger size, its impact becomes increasingly pronounced. The growing island flattens the equilibrium pressure and current profiles within the island region, which in turn reduces the local diamagnetic frequency and diminishes the mode rotation frequency accordingly. This gradual deceleration continues until the nonlinear forces driving the island growth are balanced by stabilizing effects, ultimately leading to a final saturation of both the island width and the rotation frequency. This comprehensive numerical analysis not only confirms the harmonic nature of the upper mode but also successfully reproduces the key stages of its dynamic evolution, thereby providing crucial insights into the underlying physics of mode behavior in the nonlinear regime.

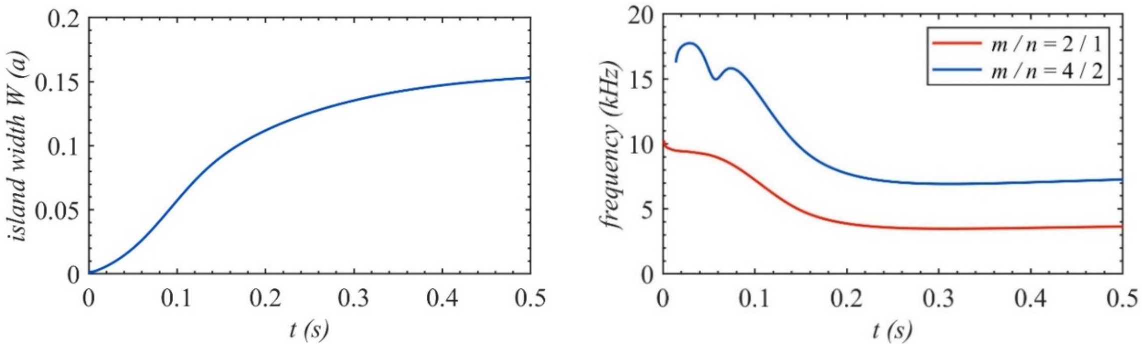

FIG. 6. (a) Temporal evolution of magnetic island width. (b) Temporal evolution of the rotation frequency of the 2/1 and 4/2 modes.

4. INFLUENCE OF KEY PARAMETERS ON ELECTRON DENSITY WINDOW

Based on the theoretical framework of the electron density window established in the preceding analysis, the competition between the driving and stabilizing terms governs the overall stability boundary. The driving term, primarily associated with the bootstrap current density gradient, exhibits a distinct broadening effect on the NTM triggering window by enhancing the free energy available for mode growth. In contrast, the stabilizing term, dominated by the electron diamagnetic drift effects, conversely constrains the operational range through wave-particle interactions that promote phase-mixing and energy dissipation. This fundamental antagonism creates the characteristic windowed stability profile observed in both simulations and experiments.

Notably, when the fraction of bootstrap current exceeds a critical threshold, the driving term overwhelms all stabilizing mechanisms, causing the density window to disappear entirely, as shown in Fig. 7. This results in unconditional NTM triggering regardless of the density parameter, representing a particularly challenging scenario for high-performance, steady-state operations in future fusion reactors. However, the introduction of sheared toroidal rotation near the 2/1 rational surface can effectively restore the density window phenomenon, as shown in Fig. 8. The velocity shear layer modifies the local mode structure and disrupts the phase coherence necessary for sustained island growth, thereby re-establishing a bounded stability region.

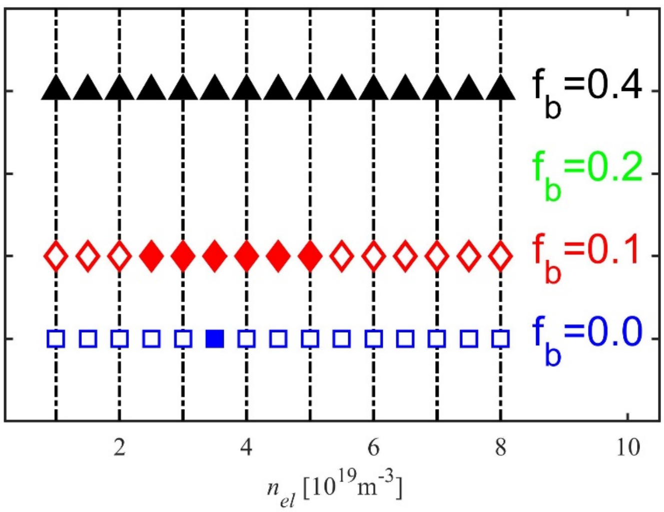

FIG. 7. The variation of the width of the electron density window under different fractions of bootstrap current.

Further enhancement of either the rotation amplitude or the rotation shear gradient, while initially beneficial, eventually leads to a progressive narrowing of the restored density window. This non-monotonic response suggests an optimal range for rotation-based control strategies, beyond which the stabilization effectiveness diminishes. Simultaneously, elevated electron beta induces a systematic shift of the density window toward higher density regimes, a favorable trend for reactor operational scenarios provided the window remains accessible within engineering constraints such as the Greenwald density limit.

Enhanced perpendicular viscosity, through its damping effect on flow structures, consistently reduces the window width by suppressing the beneficial aspects of flow shear stabilization. Interestingly, the parallel and perpendicular transport coefficients exhibit strongly non-monotonic influences on the window characteristics. Moderate increases in parallel thermal conductivity initially widen the stability window by smoothing temperature gradients, yet excessive values degrade confinement and destabilize the mode. Similarly, perpendicular transport modifications produce competing effects on both the driving and stabilizing terms, suggesting a complex interplay between different transport mechanisms that requires careful optimization for effective disruption avoidance in burning plasma environments.

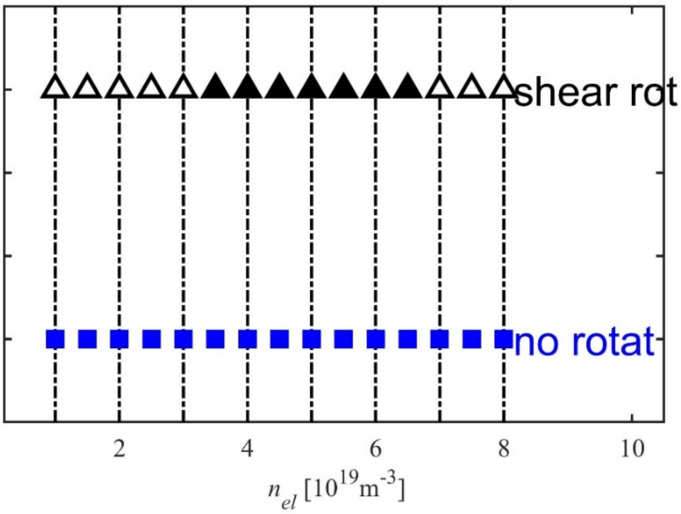

FIG. 8. The variation of the width of the electron density window with/without sheared plasma flow.

5. CONCLUSION AND DISCUSSION

The self-developed MHD code (MDC) has been successfully employed to numerically replicate the experimentally observed electron density window for neoclassical tearing mode (NTM) triggering, as reported in recent TCV tokamak experiments [1]. A series of systematic simulations demonstrate that this stabilizing window emerges within the same order of magnitude in electron density as that identified in experimental operations, confirming the robustness of the underlying physical mechanism. Both increasing the local magnetic shear near the q = 2 rational surface and raising the electron density are shown to independently trigger NTMs in the simulations, exhibiting quantitative consistency with the experimental trends observed on TCV.

Further analysis of the mode dynamics reveals that the diamagnetic drift frequency obtained from the simulations is of the same order as the experimentally measured values. During the nonlinear evolution of the mode, this frequency gradually decreases—a temporal behavior that aligns closely with experimental measurements and provides additional validation of the model's predictive capability. Theoretical interpretation using the modified Rutherford equation suggests that the observed density window arises from the modifying influence of the electron diamagnetic effect on the classical tearing mode (TM) stability index. Specifically, the diamagnetic contribution introduces a non-monotonic dependence of the stability index on plasma density, thereby creating a bounded region in parameter space where the mode is stabilized.

Parametric scans conducted over key physical quantities reveal that a larger bootstrap current fraction substantially broadens the width of the density window, indicating enhanced operational flexibility under high bootstrap-dominated scenarios. Another noteworthy finding is that elevated electron beta values induce a systematic shift of the stabilizing window toward higher density regimes. This trend is particularly favorable for future high-beta reactor operation, as it suggests the possibility of accessing stable density windows without compromising confinement performance—provided that the window remains below the Greenwald density limit.

In addition, the influence of other key plasma parameters—such as safety factor profile, pressure gradient, and current density distribution—on the density window has been systematically evaluated. These studies establish quantitative scaling relationships between plasma equilibrium properties and the stabilizing window characteristics. The resulting understanding enables the optimized utilization of the density window effect for the active avoidance of spontaneously triggered NTMs, and ultimately, for the mitigation of major disruptions in next-step tokamak devices.

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