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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

The self-developed MHD code (MHD@Dalian Code/MDC) was 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. Numerical results show quantitative consistency with experimental trends observed on TCV.

BACKGROUND

Plasma major disruptions pose a critical challenge to tokamak steady-state operation and device safety. In future reactors operating under high-confinement regimes with significant bootstrap current, neoclassical tearing modes (NTMs) are expected to become a primary cause of disruptions. While conventional control strategies aim to suppress seed magnetic islands, NTMs can also arise spontaneously without detectable seeds, presenting a greater control challenge. Recent TCV experiments have identified an electron density window that suppresses spontaneous NTMs, an effect attributed to the dual role of the electron diamagnetic effect. This work systematically investigates the underlying mechanism of this density window under high bootstrap current conditions using a self-developed, four-field reduced MHD code [2-6]. The findings aim to provide theoretical support for suppressing spontaneous NTMs and developing disruption avoidance strategies for future fusion devices.

MODEL EQUATIONS

$$\frac{\partial \psi}{\partial t} = [\psi, \varphi] - \partial_z \phi + \beta_e \delta_i (\nabla_{//} n + 2\nabla_{//} T_e) - S_A^{-1}(j - j_b) + E_{z0}$$

$$\frac{\partial u}{\partial t} = [u, \varphi] + [j, \psi] + \partial_z j + R^{-1}\nabla_\perp^2 u$$

$$\frac{\partial v}{\partial t} = [v, \varphi] - \nabla_{//}(nT_e) + R^{-1}\nabla_\perp^2 v$$

$$\frac{\partial n}{\partial t} = [n, \varphi] + 2\delta_i \nabla_{//} j - \nabla_{//}(nv) + D_\perp \nabla_\perp^2 n + S_{n0}$$

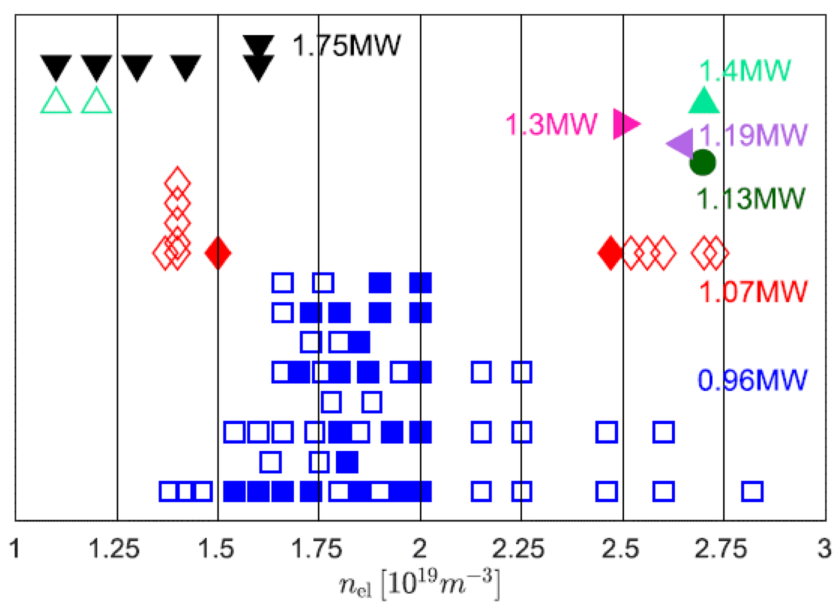
- A four-filed (magnetic flux, vorticity, ion parallel velocity, plasma density) reduced two-fluid model is adopted.
- Bootstrap current and electron diamagnetic drift effect are coupled into the model via modified Ohm's law.
- The strength of diamagnetic effect is related to the product of electron beta and ion skin depth.

CONCLUSION

- MDC simulation is carried out for the modelling of an electron density window observed in TCV experiments within which NTMs occur.
- Numerical results suggest window may be due to the modification of electron diamagnetic effect on the classical stability index of TM.
- The numerical results show the window in the same order as the TCV experiments, as well as the mode frequency and rotation direction.
- High bootstrap current largely expands the window, and stabilizing effect such as shear flow will narrow the window down.
- High electron beta makes density window deviate towards the large density direction, if beyond Greenwald limit will help to avoid NTM.

NUMERICAL MODELLING OF DENSITY WINDOW IN MDC

TCV experiment



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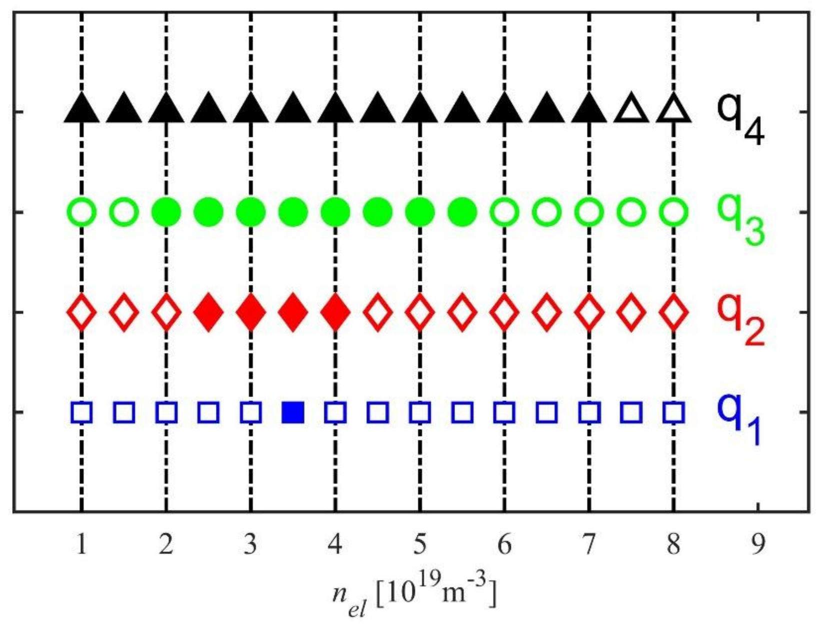
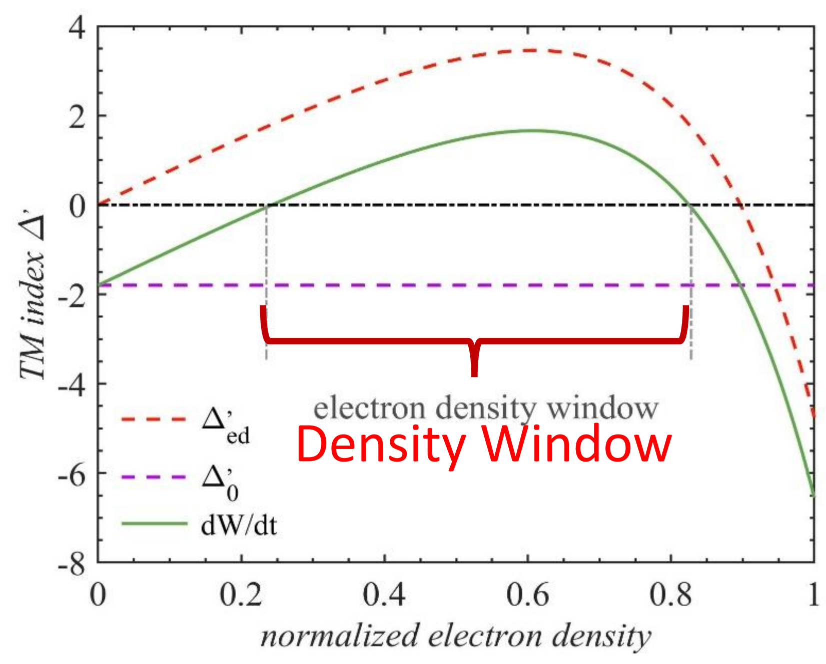
MDC simulation



In simulations, increasing ECCD power in TCV—which enhances current and magnetic shear near the q=2 surface—is modeled by a localized increase in shear at that surface, avoiding major changes to the global q-profile. Plasma density is varied via the model's ion skin depth parameter.

ELECTRON DIAMAGNETIC EFFECT IS KEY

Modified Rutherford Equation (MRE)



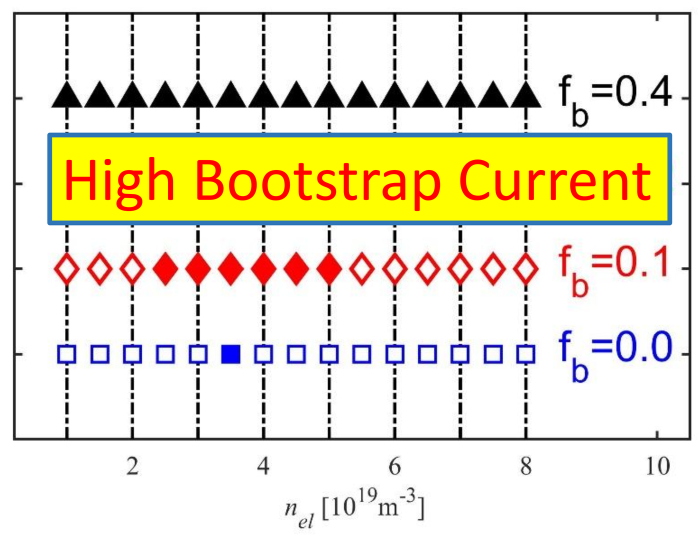
Electron Diamagnetic

$$\frac{dW}{dt} = \Delta' + \Delta'_{bs} + \Delta'_{ed} + \cdots + \Delta'_{GGJ}$$

$$\Delta'_{ed} = \Delta'_{dg}(+) + \Delta'_{df}(-)$$

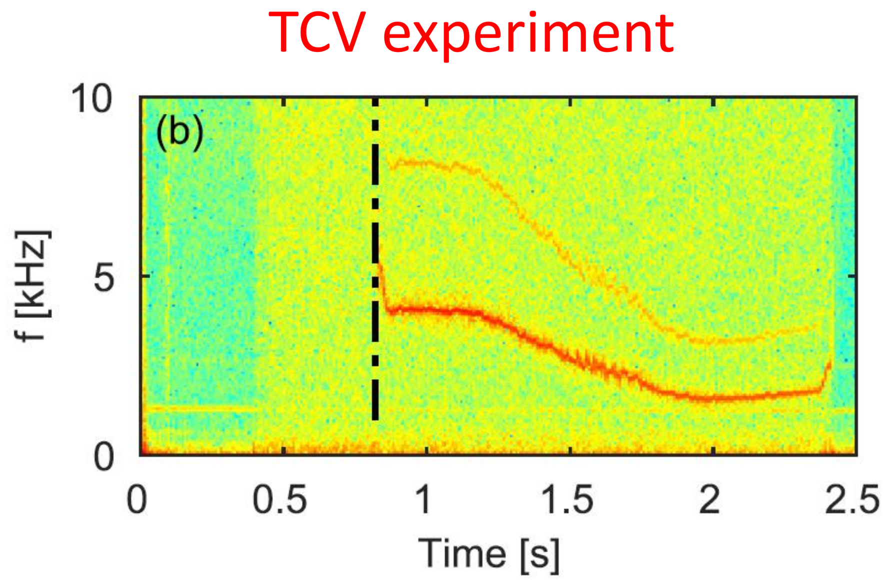
Density Gradient   Diamagnetic Flow

- MRE useful describing TM stability.
- Electron diamagnetic drift effect can be separated into two parts:
  -density gradient is a drive term
  -diamagnetic flow stabilizing term
- The density window thus can occur.



NUMERICAL MODELLING OF DENSITY WINDOW IN MDC

TCV experiment



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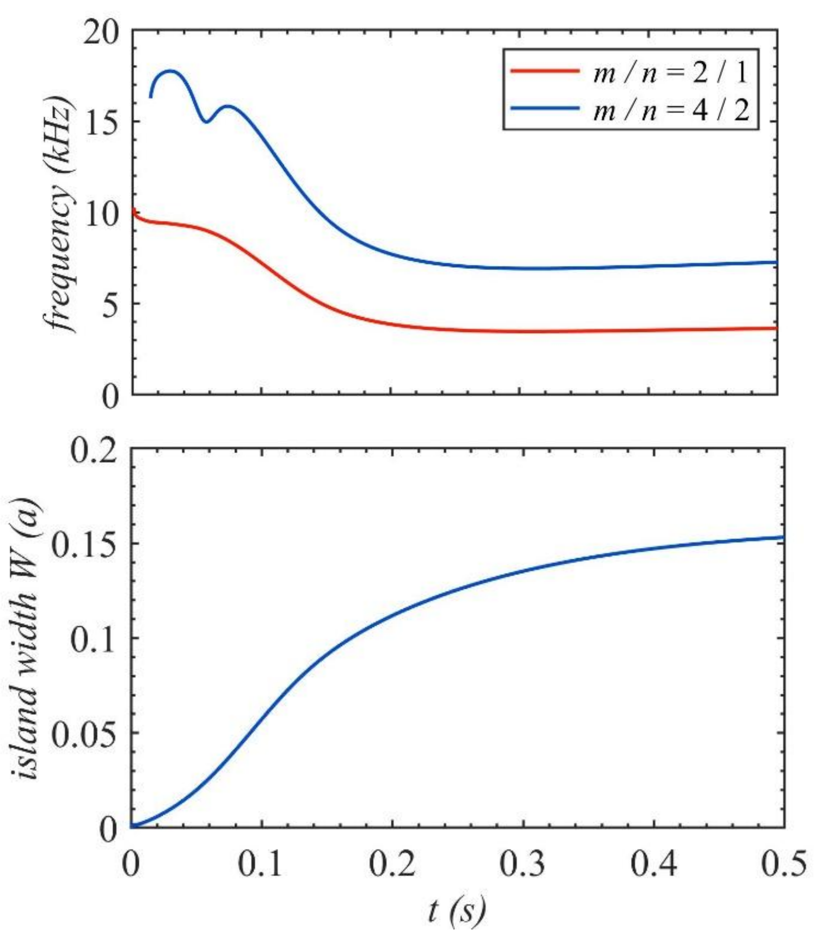
MDC simulation



- Two modes shown in experiments.
- The upper mode is 4/2 harmonic.
- In electron diamagnetic direction.
- An abrupt drop in mode frequency, attributable to drag force exerted on magnetic island structure by the surrounding plasma. A flattop phase during small island width. The system ultimately reaches saturation.

REFERENCES

[1] KONG M. *et al* Nucl. Fusion **60** (2020) 026002
[2] WANG Z.X. *et al* Nucl. Fusion **55** (2015) 043005
[3] LIU T. *et al* Nucl. Fusion **60** (2020) 106009
[4] LIU T. *et al* Nucl. Fusion **62** (2022) 056018
[5] LIU T. *et al* Nucl. Fusion **64** (2024) 036001
[6] YE C. *et al* Nucl. Fusion **59** (2019) 096044