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

[1]LIU TONG, [1]WANG ZHENG-XIONG, [1]WEI LAI, [2]WANG JIALEI

[1]Dalian University of Technology, Dalian, China
[2]National Institute for Fusion Science, Toki, Japan

Email: liutong@dlut.edu.cn

1. INTRODUCTION

Plasma major disruptions pose big threat to limit the tokamak steady-state operation and even to destroy the devices. Future fusion reactors will be operated in high confinement conditions where high fraction of bootstrap current appears, which means neoclassical tearing mode (NTM) will become the main instigator contributing to major disruptions. NTM is very dangerous for reactor-scale tokamak devices due to its harmfulness for the achievable plasma beta and its threat for leading to potential major disruptions. Given this potential economic loss by damaging experimental devices, the mitigation and/or active control of NTMs are of high priority for the performance in advanced devices such as ITER and future reactors. In general, the triggering of NTM can be avoided via eliminating the source of seed islands. However, the spontaneously growing NTM without seed islands still can be observed in many experiments. Recently, TCV experiments observed that there existed a region where spontaneous NTM can be suppressed while varying electron density [1]. The observation provides a new idea to avoid spontaneous NTM in future fusion devices. It is essential to make the best of this property for better operations of future large-scale devices. The purpose of this work is to numerically investigate the physics mechanism behind the window of electron density under high fraction of bootstrap current using self-developed 3D MHD code (MHD@Dalian) [2-3] including the electron diamagnetic effect. Aiming to provide theoretical supports to the effective suppression of spontaneously triggering NTM and thus to avoid disruption for experiments via investigating the relation between the threshold of NTM triggering and the electron diamagnetic effect, as well as the influence of different kinds of key plasma parameters on the density window.

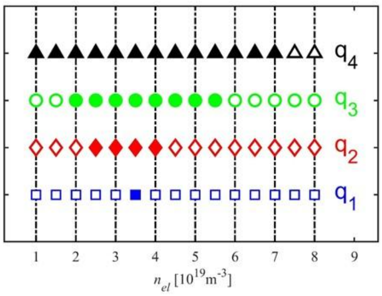
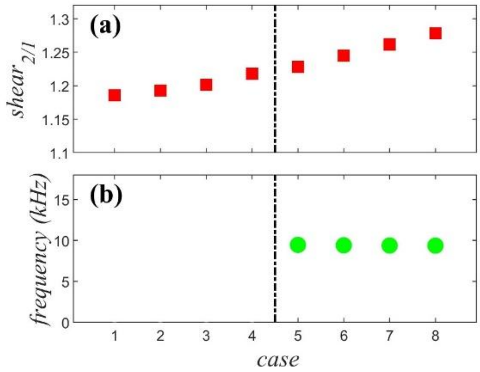


Fig. 1. Electron density window of spontaneously triggering NTM obtained via numerical simulation of MDC.

2. MODELLING OF TCV EXPERIMENTS

In this work, the plasma density is controlled via adjusting ion skin depth $\delta_i \propto 1/\sqrt{n}$ of the numerical model, while the normalized density profile is fixed. In TCV experiments, on-axis electron cyclotron current drive (ECCD) is adopted to drive plasma current. Raising EC power will increase plasma current, thus increasing magnetic shear near q=2 surface. In MDC simulation, the magnetic shear in the vicinity of 2/1 surface is modified, modelling the effect of raising EC power. Consequently, the density window can be reproduced in the MDC simulation and will expand with EC power, shown in Fig. 1. Modified Rutherford equation is adopted to analyse the density window phenomenon. Here, the effect of electron diamagnetic effect can be separated into two parts: density gradient is a drive term and the diamagnetic drift flow is a stabilizing term. With increasing density, each effect dominates one after the other, resulting in nonmonotonic influence of diamagnetic effect. Assuming a minus classical TM index, the density window will occur in the model. Linear simulations via MDC are carried out to model the EC power ramping-up experiments. As shown in Fig. 2.1, increasing magnetic shear near q=2 surface beyond a critical value, 2/1 NTM appears, reproducing the TCV experimental phenomenon [1]. The rotation is in the electron diamagnetic drift direction, the same as experiments. The rotation frequency is in the same order of the experiments and only slightly changed with increasing shear. TCV density ramping-up experiments are also modelled and reproduced via similar linear simulations, shown in Fig. 2.2. The rotation frequency and the density threshold are in the same order of experiments. The rotation frequency decreases with increasing density. Numerical results suggest that the upper mode found in the experiments is a high-order harmonic of 2/1 mode.



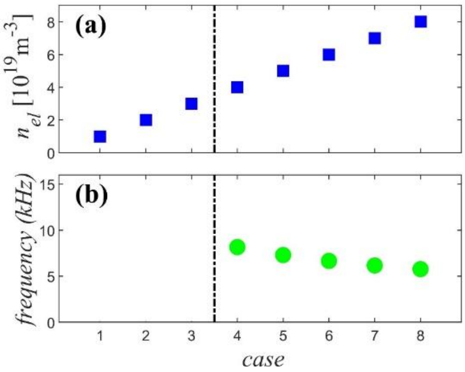


Fig. 2.1. Modelling of EC power ramp-up experiment via MDC. Fig. 2.2. Modelling of density ramp-up experiment via MDC.

3. INFLUENCE OF KEY PARAMETERS ON ELECTRON DENSITY WINDOW

Based on the theoretical framework of the density window established in the preceding analysis, the driving term exhibits a broadening effect on the triggering window, while the stabilizing term conversely constrains its operational range. Notably, for a sufficiently large fraction of bootstrap current, the density window disappears, resulting in unconditional NTM triggering. However, the introduction of sheared rotation near the 2/1 rational surface can restore the density window phenomenon. Further enhance the either rotation amplitude or rotation shear, the window will narrow down. Elevated electron beta induces a systematic shift of the density window toward higher density regimes, while enhanced viscosity reduces the window width. Interestingly, the parallel and perpendicular transport coefficients exhibit non-monotonic influences on the window characteristics, suggesting complex interplay between different transport mechanisms.

4. CONCLUSION AND DISCUSSION

The MDC simulations have been successfully implemented to model the experimentally observed electron density window for NTM triggering in TCV tokamak experiments [1]. Numerical investigations show that the electron density window exists in the same order of the experimental operation. Increasing magnetic shear or electron density can trigger NTMs, which show good agreement with the TCV experiments. The diamagnetic drift frequency is in the same order of the experimental observation and gradually decreases during the nonlinear evolution, in accordance with experiments. Theoretical analysis suggests that the density window originates from the modification of electron diamagnetic effects on the TM stability index. Parametric studies show large bootstrap current can broaden density window. Interestingly, elevated electron beta induces a shift of window toward higher density regimes, which show good favor in future high beta operation scenario, provided the window is beyond the Greenwald limit. Moreover, the influence of key plasma parameters on the window has been systematically investigated to establish quantitative relationships, enabling optimized utilization of the density window properties for the avoidance of the spontaneous NTMs and thus the major disruptions.

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