Influence of resonant magnetic perturbation on flow and turbulence dynamics towards L-H transition in HL-3

[1]M. JIANG, [1]Y. ZHANG, [2]Z. B. GUO, [1]Z. B. Shi, [3]P. H. DIAMOND, [4]W. X. GUO, [1]J. Q. XU, [1]N. ZHANG, [1]Z. WANG, [1]Z. J. LI, [1]Y. ZHOU, [1]A. S. LIANG, [1]T. F. SUN, [1]R. KE, [1]S. B. GONG, [1]X. X. HE, [1]W. CHEN AND [1]W. L. ZHONG

[1]Southwestern Institute of Physics, Chengdu, China
[2]State Key Laboratory of Nuclear Physics and Technology, Fusion Simulation Center, School of Physics, Peking University, Beijing, China
[3]University of California San Diego, La Jolla, California, USA
[4]International Joint Research Laboratory of Magnetic Confinement Fusion and Plasma Physics, State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electric and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China

Email: jiangm@swip.ac.cn

To prevent the occurrence of the first large edge localized modes, it is necessary to apply resonant magnetic perturbation (RMP) before the L-H transition. However, the application of RMP in L-mode plasmas has been observed to increase the L-H transition power threshold as observed in several fusion devices [1-3], which may inhibit access to H-mode and present operational challenges for next-generation tokamaks. This problem is particularly concerning for ITER in the Starting Research Operation phase, where the available auxiliary heating power may only marginally exceed the predicted power threshold without taking into account the effects of RMP [4]. The effect of RMP with a higher toroidal mode number n = 3 on turbulence-flow dynamics in the L-mode state before the L-H transition on DIII-D has been reported [1, 5]. In this work, a detailed analysis of the effects of n = 1 RMP on equilibrium profiles, turbulence, flow, and their interactions towards the L-H transition is investigated on the HL-3 tokamak. Furthermore, we introduce a modified one-dimensional predator-prey model that incorporates the effects of RMP to quantitatively study the turbulence-flow dynamics and the dependence of the power threshold on radial magnetic perturbation intensity.

The experiments were carried out by comparing two similar discharges, one (#6550) without RMP application, and the other (#6553) with 6.5 kA n=1 RMP. It is found that the RMP inhibits the access to H mode at 1.8 MW heating power. The profiles, flows and turbulence level at the L-mode phase (t=1722 ms) which is just before L-H transition of shot 6550 are investigated. It is found that following the RMP application, the electron density increases in the outer region (ρ > 0.85, where ρ is the normalized toroidal flux), while the electron/ion temperature decreases. The turbulence amplitude is enhanced dramatically with the RMP, while its auto-correlation time remains almost the same. The perpendicular flow (proportional to radial electric field) shear measured by the doppler backscattering reflectometer diagnostic is reduced significantly at the edge region, leading to the reduction of turbulence suppression effect by shear flow ($|\omega_{E\times B}|/\omega_D$). As depicted by figure 1, without RMP, $|\omega_{E\times B}|/\omega_D$ is close to 1 in the edge region (0.85 < ρ < 1), with some values slightly larger than 1 (ρ~0.93). This indicates that any mechanism driving additional shear flow, even transiently, would further suppress turbulence and trigger the L-H transition. However, with RMP, $|\omega_{E\times B}|/\omega_D$ decreases significantly (below 0.7) throughout the whole edge region, implying that E×B shear flow has a weaker suppression effect on the turbulence. As a result, more transient turbulence suppression is required to trigger the L-H transition, necessitating higher heating power.

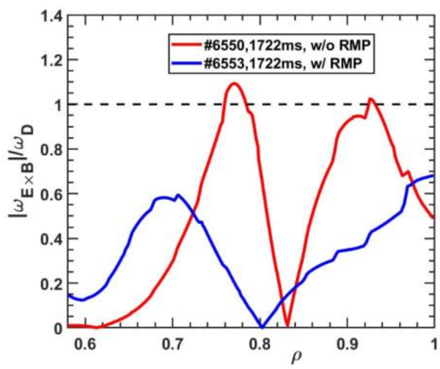

Figure 1. Turbulence suppression parameter $|\omega_{E\times B}|/\omega_D$ with and without RMP cases.

In addition, a 5-field reduced mesoscale one-dimensional (1D) predator-prey model is extended to incorporate the effect of RMP to numerically study the L-H transition dynamics [6, 7]. Here, a factor $1/(1 + \alpha)$ is introduced in the evolution equations for turbulence and zonal flow, representing the stochastic effect of Reynolds stress decoherence, where the α is proportional to the square of the strength of magnetic perturbations. It is found that the increase of magnetic perturbations leads to a significant decrease in the edge mean flow shear as shown in figure 2(a) and increase in the turbulence intensity, and delays the L-H transition, indicating that it requires more heating power to achieve the L-H transition. Moreover, we found that the power threshold Q_{LH} almost linearly enhances with the square of the strength of magnetic perturbation α, with a fitting formula of $Q_{LH} = 0.02 \times \alpha + Q_{LH,\ w/o\ RMP}$, where $Q_{LH,\ w/o\ RMP}$ is the power threshold without RMP. The result is consistent with the experimental observations in HL-3, which further demonstrates that the diminished flow shear becomes less effective in suppressing turbulence, providing a comprehensive explanation for the inhibited access to H-mode.

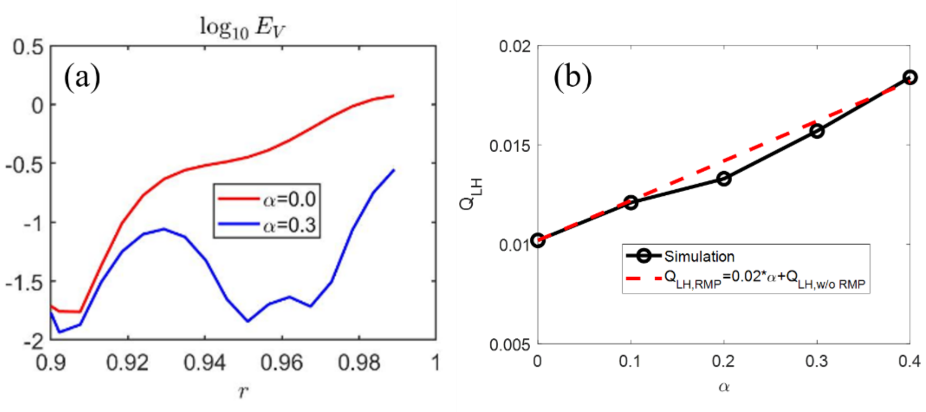

Figure 2. (a) Radial profiles of the mean square of mean flow shear before L-H transition in different α (proportional to the square of the strength of magnetic perturbations) cases. (b) L-H power threshold Q_{LH} with respective to α.

The three-dimensional perturbation introduced by RMP alters the linear instability physics of microturbulence and modify the interaction between turbulence and shear flows, further complicating the L-H transition process. These findings highlight the necessity for a better understanding of RMP-induced changes in turbulence suprresion effect, which is crucial for optimizing the operational parameters of tokamaks and enhancing the performance of future fusion reactors.

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