ADVANCES IN PHYSICS AND APPLICATIONS OF 3D MAGNETIC PERTURBATIONS ON THE J-TEXT TOKAMAK

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As of a long-term research program, the J-TEXT [1][2] experiments aim to develop fundamental physics and control mechanisms of high temperature tokamak plasma confinement and stability in support of the success operation of ITER and the design of future Chinese fusion reactor. Recent research has highlighted the significance of the role that non-axisymmetric magnetic perturbations, so called 3D magnetic perturbation (MP) fields, play in fundamentally 2D concept, i.e. tokamak. In this paper, the J-TEXT results achieved over the last two years, especially on the improved confinement with ECRH, 3D optimization for tokamak configuration, control of MHD instabilities, and plasma disruptions prediction, will be presented.

Electron thermal transport is a critical factor in magnetic confinement fusion, as fusion-born alpha particles primarily heat electrons in a reactor. For the first time, the increase of neoclassical tearing mode (NTM) amplitude has been observed to induce the reduction of the core electron thermal transport with the formation of an electron internal transport barrier (ITB) in the ECRH plasmas on J-TEXT [3]. At medium NTM amplitude, the ITB is formed with a dithering phase, i.e. plasma transitions from no transport barrier to ITB or vice versa quasi-periodically. With NTM amplitude further increasing, the dithering ITB transitions into a steady ITB. The steady ITB can last for over 0.3 s (limited by the discharge duration), which is more than 2.5 times current diffusion time. The electron temperature gradient inside ITB increases with NTM amplitude. The trigger of ITB and further enhancement of ITB performance are also demonstrated by locking the island via applying a resonant magnetic perturbation (RMP) field. The confinement energy with improved ITB can recover to the level prior to the appearance of the magnetic islands. The reduction of density fluctuations in ITB region is observed and indicates the turbulence suppression during ITB formation. These findings offer new insights for understanding ITB formation and robust ITB control.

To explore innovative approaches for optimizing tokamak configurations, a 3D external rotational transform (ERT) coil system has been installed on J-TEXT [4], experimentally realizing a Tokamak-Stellarator hybrid configuration. The ERT system induces an external rotation transform ($\iota_{\text{vac}}/\iota_0 \approx 0.1$) at the plasma edge, leading to several promising results [5]. The ERT system significantly improves MHD stability, achieving nearly 100% suppression of NTMs and 70% suppression of classical tearing modes (TMs). It also expands the operational range by increasing the maximum stable plasma current by 20% and preventing disruptions in low-q operation. Additionally, the ERT system actively suppresses runaway electrons during disruptions and functions as passive coils for disruption mitigation. In electron ITB experiments, the ERT system achieves a stable NTM-free ITB plasma while increasing core electron temperature by approximately 60%. These results demonstrate the potential of the ERT system to enhance MHD stability, operational limits, and plasma performance in tokamaks.

Stabilization of the tearing modes (TM) and locked modes (LM) are of great importance for the tokamak plasma operation. The rotating 2/1 TM can be completely suppressed by 230 kW ECRH deposited close to the rational surface [6]. The ECRH power required for LM island suppression can be reduced to 100 kW when the island’s O-point is aligned with the ECRH deposition position by applying RMP to control the phase of the 2/1 TM, and disruption avoidance by the suppression of the 2/1 LM using ECRH has been achieved [7]. The n = 2 RMP has been found to suppress the 2/1 TM after mode locking, thereby avoiding the LM disruption. The 3/1 and 4/1 are also found to affect the evolution of radiation asymmetry and lead to a 20% increase in density limit [8].

The three-dimensional island divertor configuration has been successfully implemented on J-TEXT, so as to address the heat exhaust and impurity control in tokamak. The magnetic island was generated by applying externally RMP fields, while the intersection between the edge island and the divertor target was controlled by adjusting the edge safety factor q_a, thereby establishing the island divertor configuration [9[]. During the formation of the island divertor, overall plasma confinement was maintained despite the reduction in edge confinement volume due to the presence of the island. Compared with the standard poloidal divertor, the island divertor configuration exhibited a weaker dependence on plasma current and a longer connection length, leading to a broader heat load distribution. Experimental results demonstrated that the peak heat load on the divertor target was reduced by approximately 50%, while the parallel heat flux fall-off length in the scrape-off layer (SOL) increased to 15.8~17.2 mm [12]. Furthermore, the impact of hydrogen fueling via supersonic molecular beam injection (SMBI) on divertor heat flux distribution was investigated [13]. It was observed that power detachment occurred when the radiation front approached the last closed flux surface following each SMBI pulse. In addition to heat exhaust enhancement, the island divertor configuration was found to modulate impurity radiation around the X-point of the magnetic island, which could potentially improve the stability and control of radiative divertor operation. Moreover, the island divertor exhibited promising potential for enhancing impurity screening effects. Additionally, two types of edge island instabilities were identified during divertor experiments on J-TEXT. The first, self-sustained divertor oscillations, were attributed to a sequential transition between magnetic field penetration and screening states. The second, island-healing effects, were induced by high-power ECRH [14]. These findings underscore the potential of the island divertor configuration as an effective strategy for improving heat exhaust and impurity control in tokamak operations.

Significant efforts have been made in both the disruption prediction for future tokamak reactors and the interpretability research [15]. The future tokamak reactors should be protected starting from the first discharge, therefore, an adaptive anomaly detection disruption prediction, which allowing the predictor to adapt to changes in the discharge scenario and maintain high prediction performance has been developed[16][17]. The interpretability analysis of the cross-tokamak disruption prediction shows that the model learned more consistent disruption-contributing features performed better in new tokamaks [18]. Otherwise, conflicting patterns can reduce the model performance, therefore, an instance-based transfer learning technique which trains the model using a dataset generated with the strategy involves instance and feature selection based on interpretability analysis [19]. A disruption prediction with no Greenwald fraction features has also been trained to distinguish density limit disruption from the other disruptions to learn the real density limit physics.

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