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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] experiments aim to develop fundamental physics and control mechanisms of high temperature tokamak plasma confinement and stability in support of success operation of the ITER and the design of future Chinese fusion reactor, CFETR. 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 impacts of 3D MP fields on magnetic topology, plasma disruptions, and MHD instabilities, will be presented.

In the past two years, three major achievements have been made on J-TEXT in supporting for the expanded operation regions and diagnostic capabilities. (1) The first 105 GHz/500 kW/0.5 s ECRH system has been successfully commissioned at the beginning of 2019, and the ECW with a power of more than 400 kW has been successfully injected into the plasma, increasing the core electron temperature from 0.9 keV up to around 1.5 keV. (2) The poloidal divertor configuration with an X-point in the HFS has been achieved, owing to the optimization of control strategy, the upgrading of the power supplies for divertor coils and the installation of the divertor targets in the HFS. The 400 kW ECW has also been successfully injected into the diverted plasma. (3) A 256-channel ECEI diagnostic system and two sets 4-channel DBS diagnostic have been successfully developed on J-TEXT. These diagnostics will support the future researches on the disruption physics, the turbulence, and especially the interplay between global MHD modes and turbulence.

The 2/1 locked mode (LM) is one of the biggest threats to the plasma operation, since it can lead to major disruption. It is hence important to study its formation and control. Following the previous achievement of the LM unlocking by rotating RMP [2], the electrode biasing (EB) was applied successfully to unlock the LM from either a static or rotating RMP field. Remarkably, the synergy effect of the EB and RMP field can suppress the unlocked mode completely. In the J-TEXT plasma, the coupling between 2/1 and 3/1 modes when qa approaching 3 usually leads to the growth and locking of these two modes, finally induces the disruption. By applying a moderate 2/1 RMP field, the rotating 2/1 mode is suppressed before its coupling to 3/1 mode, and hence the subsequent processes of mode coupling, locking and disruption are avoided.

In the presence of 2/1 LM, three kinds of standing wave (SW) structures have been observed to share a similar connection to the island structure, i.e. the nodes of the SWs locate around the O- or X- points of the 2/1 island. The first SW is identified to be the forced oscillation of the island phase [3] due to the application of a RMP field rotating at a few kHz (e.g. 1~6 kHz); the second kind of SWs is the so called Beta-induced Alfvén Eigenmodes (BAEs) [4] at 20 ~ 50 kHz observed with a locked or rotating island; while the third appears spontaneously at ~ 3 kHz without any external 3 kHz RMP field. The third SW might be related to the spontaneous oscillation of island phase. A systematic comparison among the three kinds of SWs might reveal the mechanism for the formation of these SWs.

The formation of locked mode in other rational surfaces, such as q = 1 or 3, is not so dangerous as the 2/1 LM, while they may be even helpful for the control of plasma. By applying an n = 2 RMP field, the 2/2 LM is excited due to the penetration of 2/2 RMP field, and then triggers the bifurcation of sawtooth behavior, characterized by the abrupt decrease of sawtooth period and magnitude. This might provide a new method on the sawtooth control. The RMP coil connection recipe has been modified in the middle of 2019, and hence allows the differential phase ($\Delta\varphi$) scan among the three rows of coils. The 3/1 RMP component with $\Delta\varphi$ = -90 degree is much larger than the previous odd parity case ($\Delta\varphi$ =180 degree), and hence successful formation of 3/1 locked island was achieved in the edge plasma at a much higher electron density (n_e = 2.5~3.5*$10^{19} m^{-3}$) compared to the previous results [5]. Especially, it is found that the 3/1 island width is reduced periodically corresponding to each sawtooth crashes.

Based on the study of 3/1 locked island, two new 3D boundary scenarios were developed, in addition to the toroidal symmetric divertor configuration. (1) The 3/1 locked island can be formed in the boundary by applying a 3/1 RMP field to a plasma with $q_a \geq 3$, forming the so called island divertor/limiter configuration. Clear 3D boundary structures were formed as observed from the tangential visible camera for the CIII radiations. The heat flux distribution, particle transport, high density operation of the island divertor will be studied in the future. (2) The non-axisymmetric helical current filaments in the SOL has been driven by placing a biased electrode in the SOL, generating a 3/1 RMP field in the boundary with an amplitude of 13 Gauss/kA [6]. This might be an attractive new method for producing an RMP field and hence for controlling plasma instabilities such as ELMs.

The control and mitigation of disruption is essential to the safe operation of ITER, and it has been systematically studied by applying RMP field, MGI and SPI on J-TEXT. When the RMP induced 2/1 LM is larger than a

critical width, the MGI shutdown process can be significantly influenced. If the phase difference between the O-point of LM and the MGI valve is +90° (or -90°), the penetration depth and the assimilation of impurities can be enhanced (or suppressed) during the pre-TQ phase and result in a faster (or slower) thermal quench [7]. During the MGI shutdown process, the runaway electron (RE) generation can be suppressed once ne is larger than a critical threshold. This ne threshold can be reduced by applying RMP field [8]. A secondary MGI can also suppress the RE generation, if the additional high-Z impurity gas arrives at the plasma edge before TQ [9]. When the secondary MGI has been applied after the formation of RE current plateau, the RE current can be dissipated, and the dissipation rate increases with the injected impurity quantity, but saturates with a maximum of 28 MA/s [10].

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