EXPERIMENTAL STUDY OF THE 2/1 MODE RMP ON THE RUNAWAY CURRENT SUPPRESSION DURING DISRUPTIONS ON J-TEXT

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Abstract

A systematic study of *m*/*n*=2/1 mode resonant magnetic perturbation (RMP) on the runaway current suppression is carried out on J-TEXT. The RMP with dominant toroidal phase is applied before disruptions which are deliberately created by massive gas injection. In the experiments, when the RMP strength is higher enough for mode penetration, the 2/1 mode island's phase could make a significant impact on the runaway current formation. The optimal islands phase for avoiding runaway electrons (REs) generation has been found to be toroidal 22.5°, where the island's O-point is close to the MGI deposition region. Moreover, the time interval between the mode penetration and the disruption, performs a distinct trend on the REs suppression. The runaway-free disruptions occur in case with long penetration durations, corresponding to larger islands，and can also be observed in the small islands case in a special RMP phase. When the width of the 2/1 mode islands is moderate, effective suppression of the runaway current becomes challenging across all four RMP phases. These results indicate that runaway current suppression should carefully consider the phase and size of locked modes, because medium-sized islands and islands with an X-point aligned with the MGI location are more difficult to suppress REs during disruptions.

1. INTRODUCTION

The runaway electrons (REs) generated during disruption may cause severe damage to the in-vessel components, posing a potential threat to the operation of tokamaks, especially for the devices with large currents [1, 2]. Thus, the avoidance and suppression of REs generation during disruption is a high priority task in future tokamaks. There are typically three methods to suppress REs, including the mass impurities injection[3, 4], the particle-wave interaction[5], and the application of external resonance magnetic perturbations (RMP)[6, 7]. The first method reduces the REs generation by increasing the critical electrical field E_c, through raising the plasma density to the Rosenbluth density[8]. However, this density is too high to achieve on the required timescale of ~10-20 ms. The second and the last methods aim to enhance the REs loss rate. When the REs loss rate exceeds the avalanche growth rate, the runaway current will be avoided. Experiments on many devices have demonstrated the effectiveness of RMP in suppressing REs. And the generation of RE current depend on both the RMP strength, mode, and phase, as well as the response of plasma. However, when the plasma response is taken into account, simulation in ITER has found that the runaway electrons are hardly to loss by the 3D field, unless a global kink instability occurs that encompass both internal and external component[9]. The gas injection could cool the plasma significantly and change the current density profile, thereby resulting in the kink instability [10]. Thus, the gas injection together with RMP could be proposed as an effective method for enhancing REs loss.

However, applying external resonance magnetic perturbation by external coils will cause mode locking when the plasma exists MHD activities, e.g. an m/n=2/1 tearing mode. Investigations has demonstrated that the pre-existing islands will significantly affect the evolution of cooling process, the appearance of higher-*n* harmonic modes and the regions of stochasticity, so that indirectly affect the REs generation[11, 12]. It has been shown that a large 4/2 harmonic of the 2/1 mode is excited in larger magnetic island in a special phase, and the TQ duration vary in different island phase[13]. JOREK simulation with pre-existing islands has found that the onset of TQ is earlier when the SPI is injected in phase with the X-point of a large pre-existing island[14]. NIMROD simulation on J-TEXT has observed that the remaining RE ratio is related to the relative toroidal phase between 2/1 mode islands and MGI valve, approximating a sine function dependence. And the optimal phase for REs loss can be attributed to the fast impurity penetration leading to a higher strength magnetic perturbation, in turn the magnetic surface become more stochastic enhancing the RE seeds loss[11]. All observations above are based on the simulation results, however, experimental evidence regarding the effect of magnetic islands on REs suppression remains unclear.

In this study, the effect of 2/1 mode islands on the runaway current formation is investigated. The resonance magnetic perturbation is applied to implant magnetic islands in a fixed phase. And the island size is adjusted by the mode penetration duration. The RMP strength, phase, and size are scanned in the experiments to explore the locking mode islands for suppressing REs. The paper is organized as follows. Section 2 presents an introduction to the experimental setup. In section 3, detailed RE suppression by RMP strength and phase in fast shutdown experiment are presented. Conclusion are presented in section 4.

2. EXPERIMENTAL SETUP

The runaway current performed on the J-TEXT tokamak was generated by the massive gas injection (MGI). The MGI valve has been installed at the bottom port of No. 9, corresponding to a toroidal phase of 225°. The low field side (LFS) mid-plane at the east is defined as 0° in toroidal and poloidal directions. The angle increases in a counterclockwise direction. Four RMP phases with an m/n=2/1 dominated mode were applied in the experiments, and their phase corresponding to a vacuum approximation is 337.5°, 157°, 189.6°, 9.6°, respectively. This RMP phase (ϕ_{RMP}) is defined as the maximum outward perturbed radial magnetic field B_r at the LFS mid-plane. The O-point phase of 2/1 mode magnetic island corresponds to the phase of the $n = 1$ mode as the peak of the poloidal field perturbation. Base on the assumption that the excited 2/1 mode magnetic islands phase is consistent with the phase of the RMP, the phase relationship between the O-point of 2/1 mode magnetic islands and the RMP phase is $\phi_{O-point} = \phi_{n=1} = \phi_{RMP} + 90°$. The poloidal relative phase ($\Delta\theta = \phi_{O\text{-}point} - \phi_{MGI}$) between the O-point of 2/1 mode islands and the MGI valve can be calculated as 11°, -79°, -62.7°, 27.3°, respectively. When the relative phase is $\Delta\theta = 0°$, the O-point of the 2/1 mode is in phase with the MGI deposition. While the $\Delta\theta = \pm 90°$, the X-point of the 2/1 mode is aligned to the MGI valve. It can be found that the MGI deposition region is close to the island's O-point in RMP phase of 337.5° and closed to the island's X-point in RMP phase of 157°.

The experimental parameters can be obtained by different diagnostics on J-TEXT. For example, the plasma temperature and cooling process can be measured by the heterodyne electron cyclotron emission (ECE) radiometer. The electron density is measured by a multi-channel polarimeter interferometer (POLARIS), which views the plasma vertically through 17 channels ranging from R = 0.81 m to 1.29 m. The magnetic perturbation during disruption was detected by the Mirnov array. The soft x-ray radiation (SXR) can be used to measure the sawtooth activities and observed the occurrence of mode penetration.

3. EXPERIMENTAL RESULT

3.1. Effect of RMP strength on runaway current

The experiments on J-TEXT are based on the target plasma with the plasma current I_p = 160 kA, the toroidal magnetic field B_T = 1.8 T and the central line-averaged electron density $n_e = 1\times10^{19}$ m^{-3}. The edge safety factor q_a is about 3.48. The MGI is triggered at 0.4 s with 5×10^{19} argon atom injected, to produce a stable runaway current plateau. The typical shots are shown in Fig. 1, including the reference short without RMP and experimental shot with RMP in phase $\phi_{RMP} = 337.5°$. About 76 kA runaway current is generated in the reference short #1056132, and it was suppressed by the RMP with a current of 2.5 kA, which corresponds to the magnetic perturbation strength of 15 Gs. When the RMP current is 1 kA, the RE current remains at 70 kA, suggesting a minor effect of weak RMP on the runaway current suppression. In the shot of #1056443 with a higher RMP strength, it can be observed that sawtooth activities in the SXR signal disappeared at 0.346 s, indicating the occurrence of magnetic islands induced by mode penetration. With the increase of penetration duration, the amplitude of ECE and SXR signal decrease simultaneously, leading to a degradation of plasma confinement before disruption. Compared to the other shots, there is a lowest core T_e in shot #1056443, which may weaken the hot-tail generation mechanism, thereby reducing the generation of RE seeds. The evolution of relative electron temperature $\delta T_e/T_e$ is shown in Fig.2. The δT_e is calculated as the instantaneous temperature variation relative to T_e. T_e is the average value measured from each channel of the ECE from $\Delta t = -0.1$ ms to $\Delta t = 0$ ms, where $\Delta t = 0$ ms corresponds to the MGI triggered time 0.4 ms. In the shot #1056443, it can be observed that the impurities penetrate more rapidly towards the q=2 surface, and gradually accumulates in the region between the q=2 surface and the q=1 surface. This process leads to a further current shrinkage, thereby initiating instability to enhance the REs loss. Due to a weak strength of RMP applied in the shot #1056440, there is no island in the plasma before disruption. And the arrival time of cooling fronts at the q=2 surface in the shot #1056440 is just a little earlier than that in the reference shot, which indicates a significant effect of islands on the impurity penetration.

The effect of RMP strengths in different phases on the formation of runaway currents have been scanned, as shown in Fig. 3. The mode penetration threshold in $\phi_{RMP} = 189.6°$ is 8 Gs, which is lower than the others RMP phase (12 Gs). In order to prevent premature disruption made by RMP, this phase RMP is triggered at 330 ms, while the other RMP phases are triggered at 310 ms. As shown in Fig. 3, the runaway current is effectively suppressed with increasing RMP strength. When the RMP strength is below the mode penetration threshold, there is poor mitigation efficient in the REs suppression. A slight increase of runaway current is also observed in the experiment, which is similar to the previous results[15]. However, this increase is not obvious, because the RMP amplitude interval in this experiment is too large to capture the detail information. When the RMP strength is 15 Gs, discharges with 337.5° RMP can suppress runaway current significantly, however, runaway current remains in discharges with other RMP phases. This result indicates the significant influence of RMP phase on the REs suppression under conditions of high RMP strength. Further increasing the RMP strength to 18 Gs, RMP with 157° can also prevent the runaway current formation, which suggests that a sufficiently high RMP strength will ultimately overcome the influence of RMP phase, thereby achieving the runaway current avoidance. Completely REs suppression was not observed in discharges with RMP phase of 189.6°. This may be explained by the limited RMP strength and the short mode penetration time for island growth. This result indicates that the suppression of runaway current related not only to the RMP strength but also to the RMP phase. When the amplitude of RMP is relatively low, the RMP phase has minimal influence on the REs suppression. However, when the RMP amplitude exceeds 15 Gs, there is an optimal RMP phase which is capable of fully suppressing the runaway current.

3.2. Effect of RMP phase on runaway current

Based on the above results, RMP with four phases was analyzed for its effect on the formation of runaway current. Because the maximum amplitude of RMP in phase 189° is 15 Gs, all RMP intensities are set to 15 Gs in the experiments. When the $\phi_{RMP} = 189.6°$ and 9.6° RMP was applied at 310 ms, disruption would occur before the MGI injection. Thus, there is a lack of discharge results at RMP phases of 189.6° and 9.6° triggered at 310 ms. Fig. 4 shows the influence of the RMP phase on the runaway current formation. It can be observed that the runaway current can be suppressed when the RMP phases are 337.5° and 9.6°. These two RMP phases correspond to the relative phases of 11° and 27.3°, where the island's O-point phase is closed to the MGI location. While the runaway current will be formed when the island's X-point is in phase with the MGI deposition. Moreover, the mitigation efficient is related to the RMP trigger time. A pre-triggered RMP will be easier to avoid the runaway current generation. However, a later-triggered RMP such as 340 ms, runaway current is remained in discharges with four RMP phases. A pre-triggered RMP could causes earlier mode penetration, thereby amplifying the island size over time. Bigger islands are more likely to facilitate the suppression of runaway current because of the degradation of plasma confinement before disruption and a large region of stochasticity formed during disruption. One outlier with RE current was observed with 337.5° RMP triggered at 330 ms, which can be interpreted as a latter mode penetration leading to the formation of relatively small island. Fig. 5 presents the result of the conversion rate of runaway current under various RMP phases and different mode penetration times. It can be observed that when the mode penetration happened before 0.36 s, the REs suppression is significantly related to the RMP phase. However, when the mode penetration happened after 0.36 s, there is no obvious trend between the REs suppression and the RMP phase. These results indicate that the phase of magnetic islands (or RMP phases) significantly affects the RE suppression only when the island width is sufficiently large.

3.3. Effect of RMP trigger time on runaway current

The RMP trigger time, related to the island size, can significantly impact the REs suppression. Thus, a detailed scan of the RMP trigger time was carried out, as shown in Fig. 6. The RMP phase was selected as 337.5° and 9.6°, where the O-point of 2/1 mode island is closed to the MGI location. In Fig. 6, the horizontal axis represents the mode penetration time, which is defined as the time at which the oscillations of the core ECE signal disappeared. It can be seen that the RE current gradually decreases with the increase of mode penetration duration, and finally suppressed when the mode penetration occur before 0.35 s. The mode penetration duration is calculated by subtracting the mode penetration time from the MGI trigger time (0.4s), which is 50 ms in the experiment for a reliable REs suppression. In Fig. 6(b), there are two ranges for runaway current suppression in RMP phase of 9.6°. One range is the mode penetration durations longer than 50 ms, and the other is the mode penetration occurring at approximately 0.4 s. The first range is same to the case of 337.5° RMP, however, the other is different. The second regime corresponds to a small island, which is capable of achieving RE avoidance in the RMP phase of 9.6°, but not in the phase of 337.5°. This may be interpreted as the different spectrum of RMP applied, where a larger amplitude of n=3 mode exists in the RMP phase of 9.6°. Investigation has found that the small island has the ability to excite high n mode islands during disruption, and those modes may be amplified by the RMP, further disturbing the magnetic surfaces in plasma core and thereby suppressing the runaway current [12]. In both RMP phase of 9.6° and 337.5°, the runaway current is hard to be suppressed when the island size is moderate. This may be explained by the intact magnetic surface confined more REs seeds during disruption [16]. The results above indicate that impurity injection for the RE suppression will be difficult to achieve when the island size is medium. Due to location of ECE diagnostic, the island width in these two island phases was not detected. However, we can get some insights from the previous result that as long as the island size larger than 4 cm (0.16 times the small radius), the runaway current can be fully suppressed [17]. These results could offer some valuable insights into mitigating locking mode disruptions, including the appropriate width of islands and the most effective deposition location for MGI.

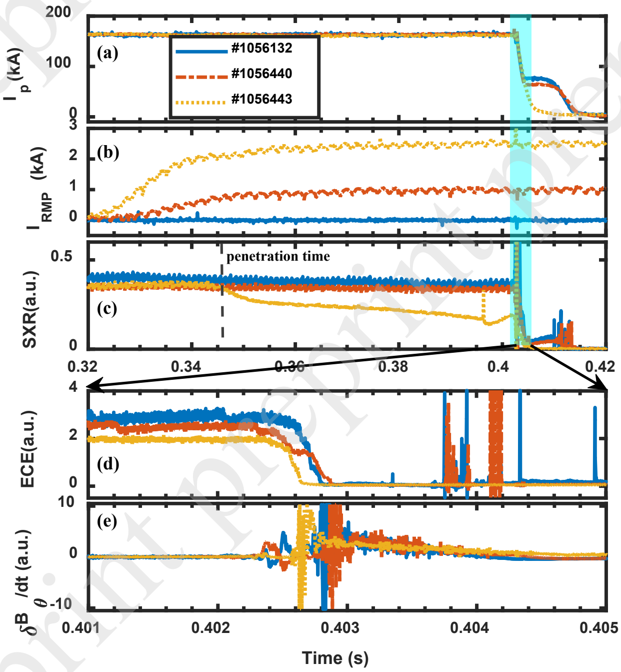

Figure 1 Temporal evolution of typical shots in J-TEXT, Ar MGI is triggered at 0.4s. From the top to bottom, the waveforms are: (a) the plasma current, (b) the RMP current, (c) the core SXR signal, (d) the core ECE signal, (e) Mirnov signal. The dash line in (c) represents the time of mode penetration.

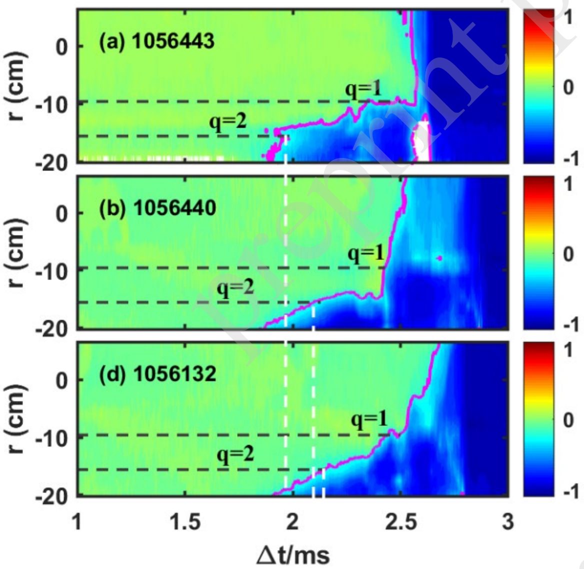

Figure 2 The profile of relative electron temperature. The black dash lines represent the q=2 and q=3 surfaces, while the white dash lines indicate the arrival times of the cooling fronts at the q=2 surface. Δt denotes the relative time, where 0 ms corresponds to the MGI-triggered time at 0.4 ms.

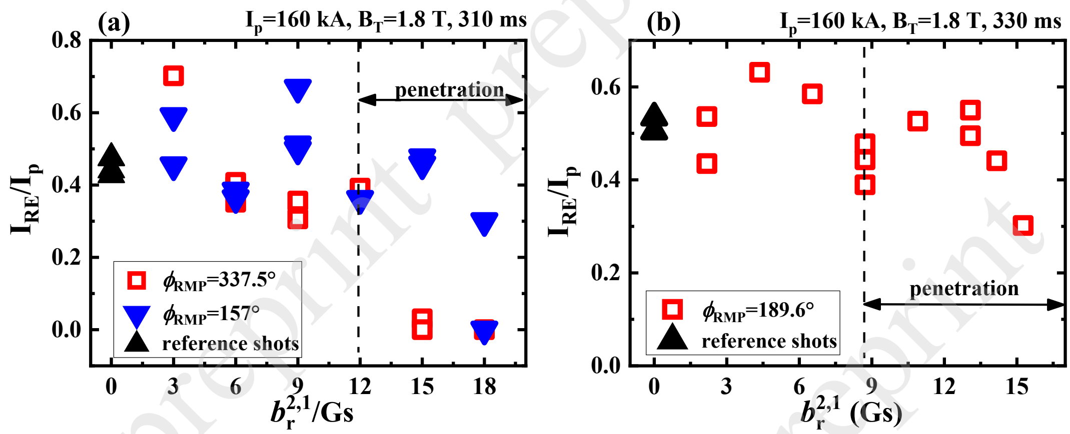

Figure 3 The relationship between the RMP strength and the runaway current convention rate (I_{RE}/I_P) in different RMP phase. (a) RMP is triggered at 310 ms; (b) RMP is triggered at 330 ms.

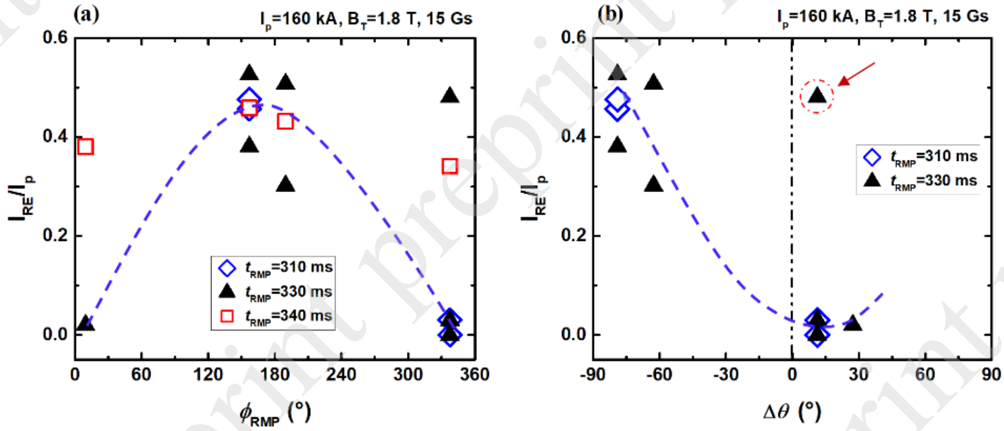

Figure 4. The relationship between the runaway current conversion rate and (a) the RMP phase, (b) the relative phase. The blue dashed line indicates the fitted trend. The black double dash-dot line in (b) represents the O-point of 2/1 mode island that is in phase with MGI deposition. The runaway current generated in shot (indicated by the arrow) can be attributed to the insufficient mode penetration duration.

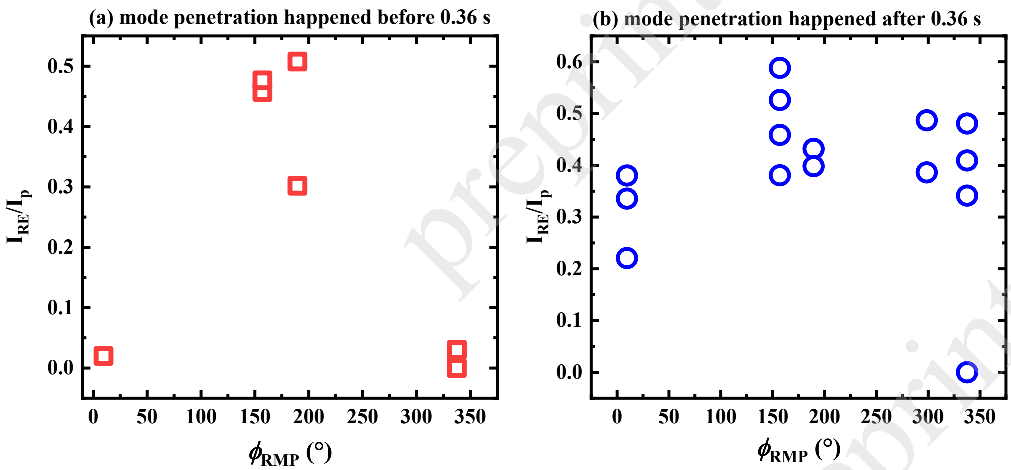

Figure 5 The relationship between runaway current conversion rate and the RMP phase. (a) the mode penetration happened before 0.36 s; (b) the mode penetration happened after 0.36s. There is a runaway free discharge in figure (b), which may be a critical case in this RMP phase for RE suppression.

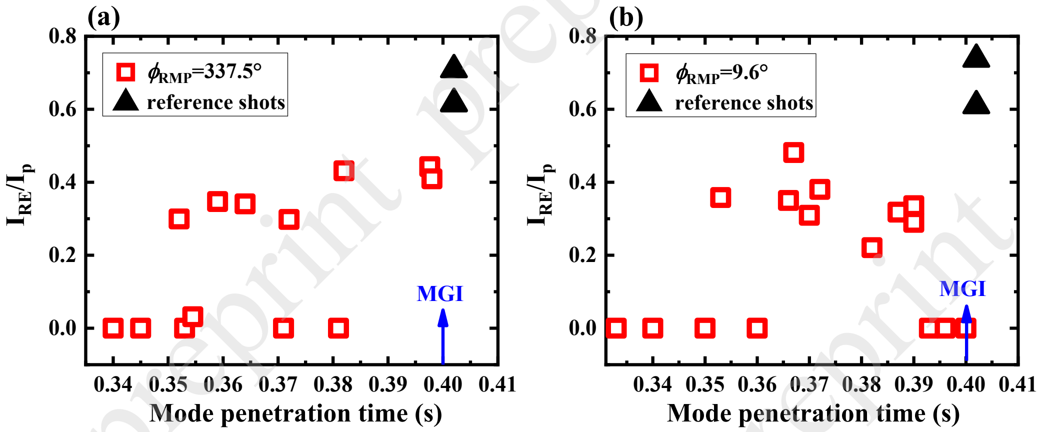

Figure 6 The relationship between the modes penetration time and the conversion rate of plasma current to runaway current when the RMP phase is (a) 337° and (b) 9.6°, respectively. The MGI is triggered at 0.4 s.

4. CONCLUSION

The suppression of runaway current by the 2/1 mode RMP has been carried out on J-TEXT. It has been observed that when the RMP strength is high enough for mode penetration, the pre-existing islands with a fixed phase can significantly influence the RE current generation. The runaway current can be more easily avoided when the O-point of 2/1 mode islands is located close to the MGI position. This may be interpreted as the growth of magnetic perturbation during disruptions, which is caused by the pre-existing islands being amplified by impurities. Impurity injection could cool the plasma quickly and cause local pressure gradient disturbances, which in turn lead to local current density disturbances and the formation of magnetic islands. The O-point of these islands has been demonstrated to be in phase with impurity deposition. Thus, the stimulated island and the pre-existing island will easily overlap. Moreover, as impurities penetrate further inside, the pre-existing islands will be destabilized, leading to larger islands and higher magnetic perturbations. Ultimately, a large region of stochasticity will form and promote the loss of REs during disruption. When the islands size before disruption is insufficiently large, the promoting effect of the island phase on REs suppression becomes minor. In the experiments, it is difficult to prevent runaway current generation when the island size is medium. These islands may confine more REs seeds during disruption due to the intact magnetic surface. When the RMP strength is sufficiently high, the runaway current can be avoided even though the X-point of the 2/1 mode island is aligned with the MGI. A higher strength RMP will promote a fast growth of islands and generate larger islands within the same penetration duration. This result may suggest that a larger island would be needed for the RE suppression when the X-point of 2/1 mode island is close to the MGI valves. Those results may provide some insight into the locking mode disruptions, in which the phase and width of islands can be optimized to efficiently suppress runaway current.

ACKNOWLEDGEMENTS

The authors are very grateful to help with J-TEXT team. This work was supported by the National Natural Science Foundation of China (No. 12205122), the State Key Laboratory of Advanced Electromagnetic Technology (No. AET 2025KF017) and the Hubei International Science and Technology Cooperation Projects (No. 2022EHB003).

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