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OVERVIEW OF PLASMA DISRUPTION MITIGATION ON J-TEXT TOKAMAK

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Abstract

The mitigation of disruption is a critical issue for the safe operation of tokamak. In recent years, many works about disruption mitigation have been carried on J-TEXT tokamak. First, the massive gas injection (MGI) and shattered pellet injection (SPI) have been developed for disruption mitigation. The novel electromagnetic pellet injection (EMPI) system based on the railgun concept, has been developed and will applied on J-TEXT soon. Second, two strategies for the mitigation of runaway electron beam have been applied in experiments. The first strategy enables the REs to be completely suppressed by means of supersonic molecular beam injection (SMBI) and resonant magnetic perturbation (RMP) which can enhance REs loss, and the secondary massive gas injection which can increase the collisional damping. For the second strategy, the runaway current will be allowed to be formed but should be dissipated by impurity injection. It has been observed that the runaway current can be significantly dissipated by MGI, and the dissipation rate increases with the injected impurity particle number and eventually stabilizes at 28 MA s^{-1}. On the other way, the mixed deuterium-neon pellet has been injected by SPI during the runaway current plateau, which successfully extended the runaway current plateau. Third, an m/n = 2/1 locked mode induced by RMP penetration during the plasma shutdown by MGI and SPI, there is a close to sine function relationship between toroidal peaking factor (TPF) and the phase of 2/1 tearing mode. The results of the disruption mitigation provide an important insight on the disruption mitigation for the future large tokamaks.

1. INTRODUCTION

A disruption in tokamak is a sudden termination of plasma discharge, imposing substantial thermal loads and electromagnetic forces on the surrounding structures, but also generates runaway electrons (REs) which can burn holes through structures [1-2]. Disruptions are almost inevitable in tokamaks, there will always be a non-zero probability of some off-normal event setting off a sequence of events that leads to a disruption [3]. The operation of large-scale devices should minimize the occurrence of disruptions and mitigate their consequences to the greatest extent possible when they occur. Therefore, the mitigation of disruption is a critical issue for the safe operation of tokamaks. To reduce the damage caused by thermal loads and electromagnetic forces, two main methods are used: massive gas injection (MGI) and shattered pellet injection (SPI). These techniques are essential for minimizing disruption impacts and ensuring tokamak safety. While the suppression of REs remains uncertain because a large runaway current will be formed even if only a few RE seeds survive during disruption. Significant progress has been made in recent years in disruption mitigation on J-TEXT by mitigation systems, especially the suppression and dissipation of REs [4].

This paper reviews recent achievements in plasma disruption mitigation on the J-TEXT tokamak, including the development of disruption mitigation systems, the suppression and dissipation of runaway currents generated after disruptions by impurity injection, magnetic perturbation, as well as studies on toroidal radiation asymmetry during plasma disruption under impurity injection.

2. DEVELOP OF DISRUPTION MITIGATION SYSTEMS

To study the plasma fast shutdown and disruption mitigation experiments on J-TEXT, two massive gas injection (MGI) valves have been developed on J-TEXT [5-6]. As shown in Fig. 1, one 30 ml MGI valve (MGI1) with the range of 5–30 bar, located at the bottom of port 9, is used to trigger major disruptions and achieve a stable runaway current. Another 60 ml MGI valve (MGI2) with the range of 5–40 bar, positioned at the top of port 9, can be used to dissipate the runaway current. The MGI valve is based on the eddy-current repulsion mechanism. The piston of the MGI valve is made by nonferromagnetic material, so it can be installed close to the vacuum vessel which has a strong toroidal magnetic field. The drive coil of the valve is installed outside the gas chamber. Owing to the large electromagnetic force the reaction time of the valve is shorter than 0.3 ms. Duration for the opening of the MGI valve is in the order of 10 ms. The MGI valve can keep opening in the order of 10 ms. The maximum density of the injected purities is more than 100 times the plasma inventory.

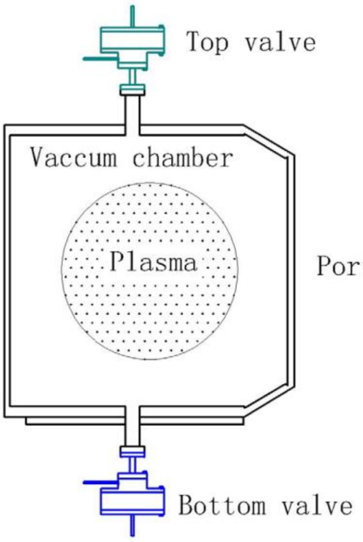

Fig. 1 Schematic view of the MGI valves on J-TEXT

To support the SPI task force of international tokamak physics activity (ITPA), a SPI system, focusing on disruption mitigation has been designed for the J-TEXT tokamak [7]. This advanced SPI system can produce argon/neon/deuterium with 5 mm in diameter and 4-8 mm in length. A key feature is its flexible velocity adjustment, ranging from 150-300 m/s, achieved by setting the propellant gas pressure. The performance of disruption mitigation by Ar SPI has been compared with Ar MGI. The cooling process observed from the ECE indicates that the SPI has deeper deposition, with the cold front that can reach the q = 1 rational surface in case of SPI, but stops at the q = 2 profile in MGI. The increase of core plasma density during a fast shutdown is higher than that with Ar MGI, which proves a deeper penetration of SPI [8]. Changing the pellet velocity can effectively adjust the TQ process and CQ rate, which can achieve a higher impurity assimilation rate when the pellet velocity increases in a certain range.

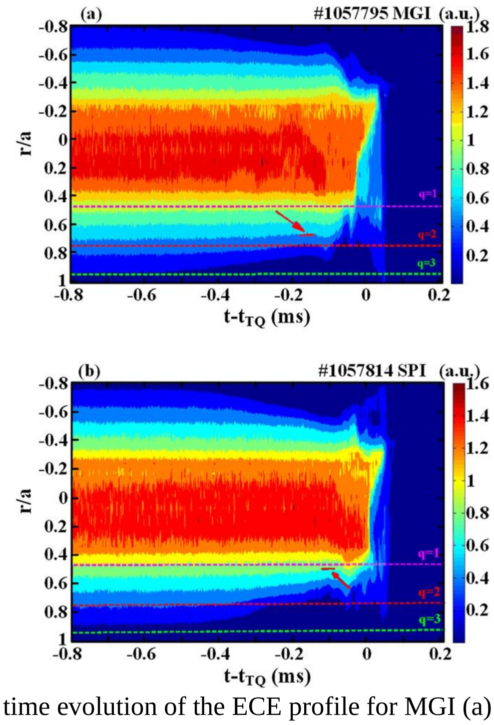

Fig. 5 The time evolution of the ECE profile for MGI (a) and SPI (b)

When extrapolating to ITER-like tokamaks, long overall reaction duration and shallow penetration depth due to low injection speed make it stricter for plasma control system to predict the impending disruptions. Some disruptions with a short warning time may be unavoidable. Thus, a fast time response and high injection speed disruption mitigation system (DMS) is essential for large scale devices. The J-TEXT team has developed the electromagnetic pellet injection system (EMPI). Based on the railgun concept, EMPI can accelerate the payload to over 1000 m/s and shorten the overall reaction time to a few milliseconds. To verify the injection ability and stability of the EMPI, the prototype injector EMPI-1 has been designed and assembled. The preliminary test has been carried out using a 5.9 g armature to propel a dummy pellet and the results suggest that the EMPI configuration has a great potential to be the DMS of the large scale fusion devices [9-10].

Fig. 3 EMPI-1 prototype test platform

3. SUPPRESSION AND DISSIPATION OF RUNAWAY ELECTRONS

Effective disruption mitigation is a key issue in the safe and reliable operation of future tokamaks. Approaches aimed at suppressing and mitigating runaway current formation by MGI, SPI, supersonic molecular beam injection (SMBI) and resonant magnetic perturbation (RMP) have been investigated in J-TEXT [11-16].
In the previous experiment, the hydrogen SMBI can provoke significant magnetic perturbation in the plasma current flattop, which has been applied to suppress the generation of REs during disruption phase [11]. Complete suppression of REs is realized by H_2 SMBI with an earlier trigger time or sufficient H_2 quantity, in which SMBI provokes significant magnetic perturbation that destroys the intact magnetic surface in the core and enhances loss of REs during disruption. The typical results are shown in Fig. 4 and Fig. 5. This phenomenon may be interpreted as the variation of amplitude and spread region of magnetic perturbation in the plasma.

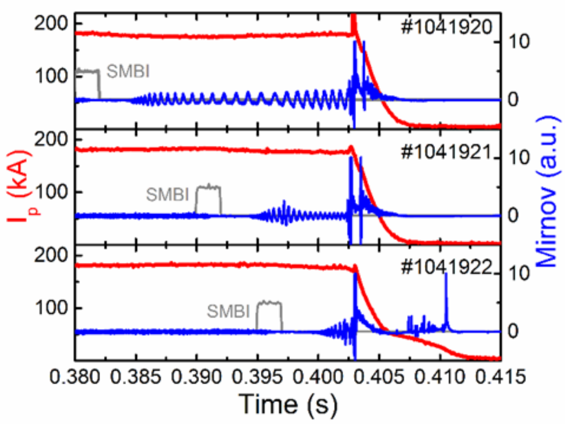

Fig. 4 The suppression of runaway current with different SMBI injection times

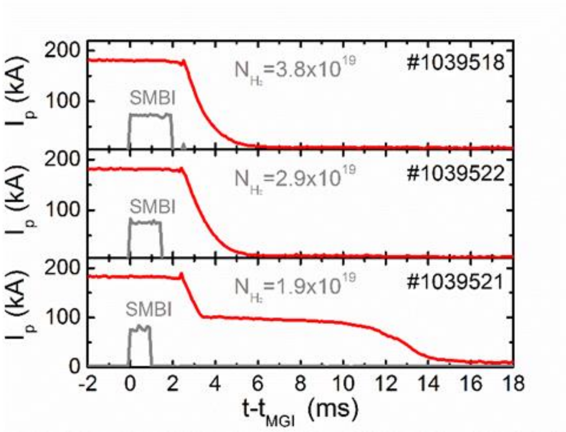

Fig. 5 The suppression of runaway current with different SMBI gas quantities

The large magnetic islands implemented by mode penetration and mode locking can act as explosive bombs during disruptions and lead to stronger stochasticity in the whole plasma cross section. It has been observed that the runaway current can be fully avoided by applying m/n = 2/1 mode RMP before thermal quench, and the efficiency of REs suppression is related to the trigger time of RMP (Fig. 6) which enlarges magnetic islands to form a stronger stochasticity in the whole plasma cross section during disruption. Base on the different plasma condition with/without MHD activity, two cases have been investigated on the J-TEXT tokamak. For the mode locking case, robust suppression of runaway current has been reached as long as the mode locking occurred 4 ms before disruption [12-13], and the runaway current has been just partially suppressed with partial mode locking. The stationary magnetic islands resulted from mode locking, has increased its width over the locking duration until saturation.

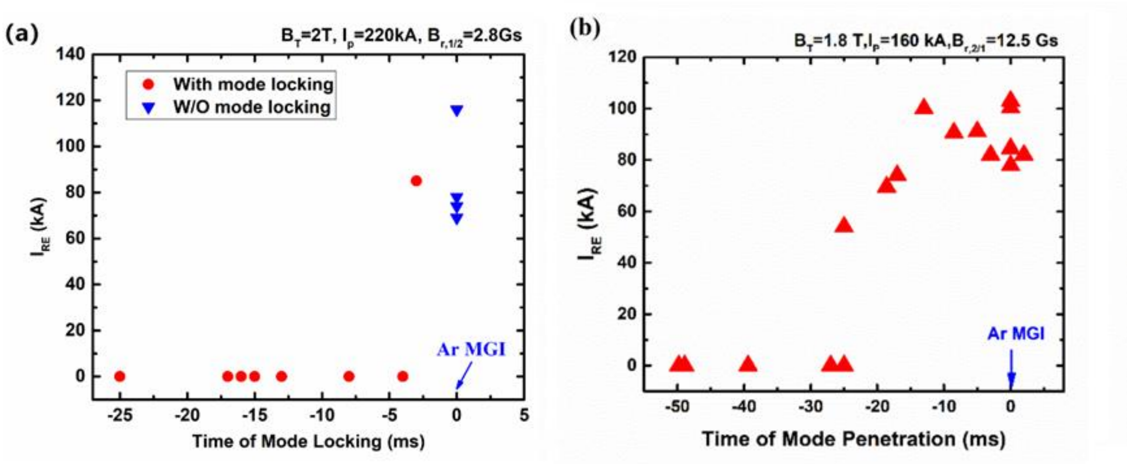

Fig. 6 The relationship of the runaway current on the time of (a) mode locking and (b) mode penetration before the disruptions

For the reliable and effective suppression of runaway current, a secondary massive gas injection (MGI2) from another valve with a delay time has been performed on J-TEXT [14]. The experimental result is shown in Fig. 7. Runaway current has been produced by Ar MGI which triggered at 0.4 ms, and the impurities used in MGI2 are argon. It has been found that when the secondary impurity gas arrived the plasma edge before TQ, the generation of runaway current has been completely suppressed. However, if the secondary impurity gas arrives the plasma edge during CQ phase, the generation of runaway current has been partly suppressed. This result maybe account for the different generation mechanism of REs during TQ and CQ phase.

For large-scale devices, a cascade strategy for the control of runaway current is essential. Consequently, the runaway current should be robustly dissipated or soft landed to minimize damage to critical components of the device. Dissipation of runaway current by high-Z impurities injection has been carried on J-TEXT [15]. The runaway current plateau has been induced and formed by the first Ar MGI, and has been dissipated by the secondary Ar/Kr MGI. The dissipation efficiency of runaway current, characterized by the decay rate of runaway current (dI_{RE}/dt), has been found to increase with the increase of runaway current and quantity of injected impurity, and reaches a stable value with a maximum of 28 MA s^{-1}, as can be seen in Fig. 8.

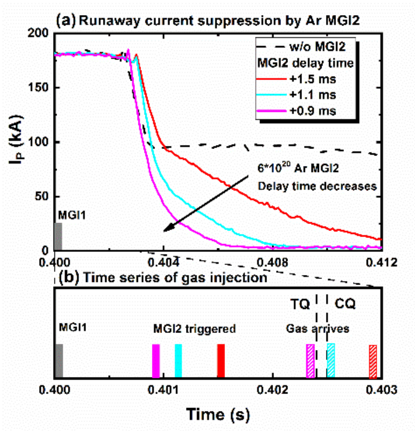

Fig. 7 The suppression of runaway current by MGI2 injected with different delay times. (a) Time evolution of current caused by Ar MGI2, (b) the time sequence of MGI1 trigger, MGI2 trigger, MGI2 arriving at plasma edge

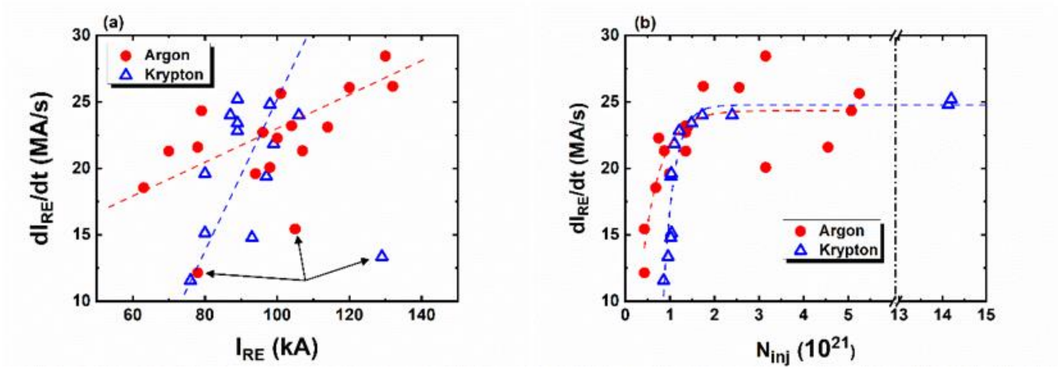

Fig. 8 The relationship between runaway current dissipation rate and (a) the runaway current and (b) the injected impurity quantity Ninj

SPI, as a new disruption mitigating technology, is found to have a deeper penetration and a higher assimilation than MGI, which is inspiring for applications in the future. High-*Z* impurities, such as argon, used for disruption mitigation may lead to difficulties in plasma discharge recovery and the generation of runaway currents. Utilizing low-*Z* impurity injection to mitigate runaway currents may be a preferable option. On the J-TEXT tokamak, the mixed deuterium-neon pellet has been injected by SPI during the runaway current plateau, which successfully extended the runaway current plateau. This will be beneficial for the benign termination of runaway currents, as shown in Fig. 9. The underlying mechanism is possibly that the low-*Z* impurities displace the high-*Z* argon, causing a fraction of the high-energy runaway electrons enter the low-energy range, and detected by electron cyclotron emission (ECE).

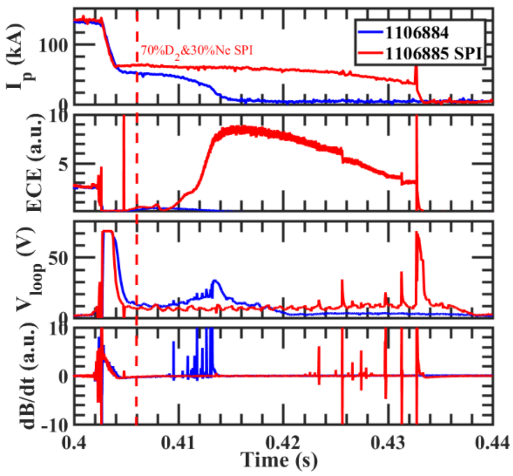

Fig. 9 Runaway current mitigation by SPI with mixed deuterium-neon pellet

4. RADIATION ASYMMETRY DURING DISRUPTION

From the experimental results, the destabilization of low-order MHD modes has been observed to grow rapidly when the gas-jet-initiated cold front reaches the vicinity of the corresponding rational surfaces during fast shutdown by an MGI. In addition, the toroidal phase of peak radiated power can be determined by low-*n* MHD modes. On the J-TEXT, an $m/n = 2/1$ locked mode induced by RMP penetration was terminated by MGI and SPI, the penetration depth and assimilation of impurities are suppressed, leading to a slower TQ when the relative phase is = −90°, and there is a close to sine function relationship between toroidal peaking factor (TPF) and the phase of 2/1 tearing mode [17-18]. The results suggest that the 3D effect between the injected impurities and the 2/1 locked mode is important during the disruption mitigation process.

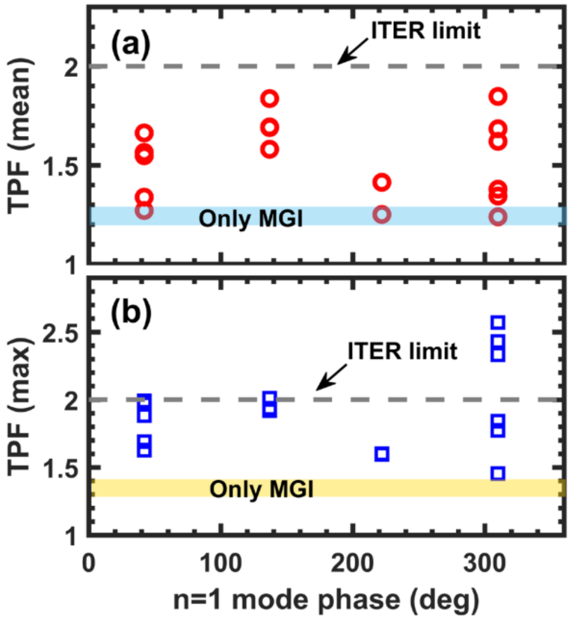

Fig.10 The TPF during the TQ phase for different mode phases, (a) the mean value and (b) the max value during the TQ phase.

5. CONCLUSION

The experiments of disruption mitigation on J-TEXT have been carried on, including suppression and mitigation of REs, radiation asymmetry during disruptions. In terms of REs suppression, the REs can be completely suppressed by means of supersonic molecular beam injection and resonant magnetic perturbation which can enhance RE loss. For the formed runaway current, which can be significantly dissipated by MGI with high-*Z* impurities, and the dissipation rate eventually stabilizes at 28 MA s^{-1}. On the contrary, low-*Z* impurities injected can extend the runaway current plateau and achieve a benign termination of the runaway current. At the same time, the results during plasma shutdown by MGI and SPI suggest that the 3D effect between the injected impurities and the 2/1 locked mode is important during the disruption mitigation process. Those will be helpful for the study of disruption mitigation of future large fusion devices.

ACKNOWLEDGEMENTS

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