THERMAL QUENCH DYNAMICS AND HEAT FLUX DISTRIBUTION DURING MASSIVE-IMPURITY-INJECTION TRIGGERED DISRUPTION IN EAST

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Thermal quench (TQ) dynamics in massive-gas-injection (MGI) triggered EAST disruptions, including reversion of magnetic-island's rotation direction in the pre-TQ phase, staged cooling and 3D splitting of heat flux during the TQ phase, have been experimentally demonstrated. 3D non-linear MHD simulations are performed using the JOREK code. Simulation results show that the radial electric field induced by localized pressure perturbation could cause the mode rotation and heat stripes are attributed to mode-induced additional magnetic connections to the divertor. These findings can enhance the understanding of the impurity influx and the heat flux deposition during mitigated disruptions.

Rotation direction of magnetic island is observed to reverse in the pre-TQ phase when large amount of neon is injected into co-current NBI-heating plasmas, as shown in Fig. 1(a). After impurity injection at 6 s, the 2/1 mode's rotation slows down and then reverses from the ion diamagnetic to the electron diamagnetic direction [1]. The mode frequency changes from 2 kHz to −2 kHz in ~ 1 ms. Furthermore, more impurity injection can enhance the reversal process. In the RF-heating plasmas, the mode rotates only in the electron diamagnetic direction. Meanwhile, similar geometrical structure of impurity radiation has been observed in bolometer measurement, shown in Fig. 1(b). The radiation is initially localized near the plasma boundary after impurity injection. However, the radiation in the core region significantly increases following the rotation direction of the mode reversed. These results suggest that the impurity penetration accompanied by mode rotation could lead to inward propagating plasma cooling. Besides, these phenomena have also been found in SPI triggered disruptions on EAST.

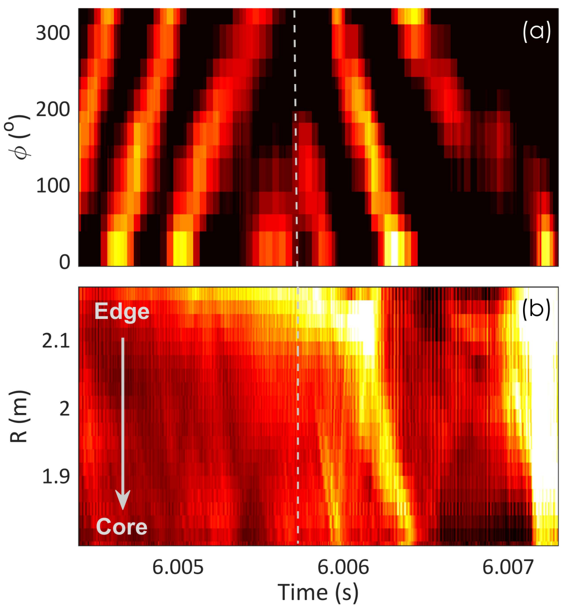

FIG. 1. (a) Time evolution of n = 1 MHD modes, and (b) contour plot of bolometry measurements. The dashed line indicates time for rotation reversion.

The hybrid-kinetic version of JOREK has been used to simulate this process [2]. A radial electric field with the inward direction is found with neon injection in the simulation, which is caused by the discrepancy between the localized pressure perturbation and the magnetic flux surfaces. Coupled with the toroidal magnetic field, the radial electric field further drives a plasma rotation as well as an impurity drift along the electron diamagnetic direction. When the rotation is large enough to overcome the NBI-driving rotation along the ion diamagnetic direction, the mode becomes observable along the electron diamagnetic direction. The radial electric field can also drive inward flux of impurity and then enhance radiative cooling. The observed radiation evolution (Fig. 1(b)) serves as evidence for the existence of this field. These findings suggest that the inward electric field provides an explanation for impurity influx and may also suggest potential strategies for disruption mitigation.

Staged cooling in the TQ phase, mainly including the single-stage TQ and double-stage TQ, has been identified in EAST disruptions. A single-stage TQ is characterized by a faster growth rate (1.5×10^{-2} μs^{-1}) of MHD activities compared to a double-stage TQ (5.3×10^{-2} μs^{-1}) [3]. In a double-stage TQ, the thermal energy loss time becomes shorter with increased impurity, leading to the merging of the 1–2 delay stage and the fast quench stage into a single-stage TQ. JOREK simulation has reproduced both the double-stage and single-stage TQ process by varying impurity particle fluxes. The growth of the m/n = 2/1 mode leads to the transport loss in the core plasma, corresponding to the first temperature collapse in the double-stage TQ. This collapse releases a fraction of the free energy, moderating subsequent MHD instabilities. Prior to the fast quench, the non-linear interaction between the 3/1 and 2/1 modes primarily leads to global stochastic, corresponding to the second collapse. The transition between the single-stage TQ and double-stage is dominantly determined by the n = 1 mode growth rate. In terms of the energy spectrum, cases with a greater quantity of injected gas particles exhibit a more rapid growth rate of the n = 1 mode, which has been verified in the experiment.

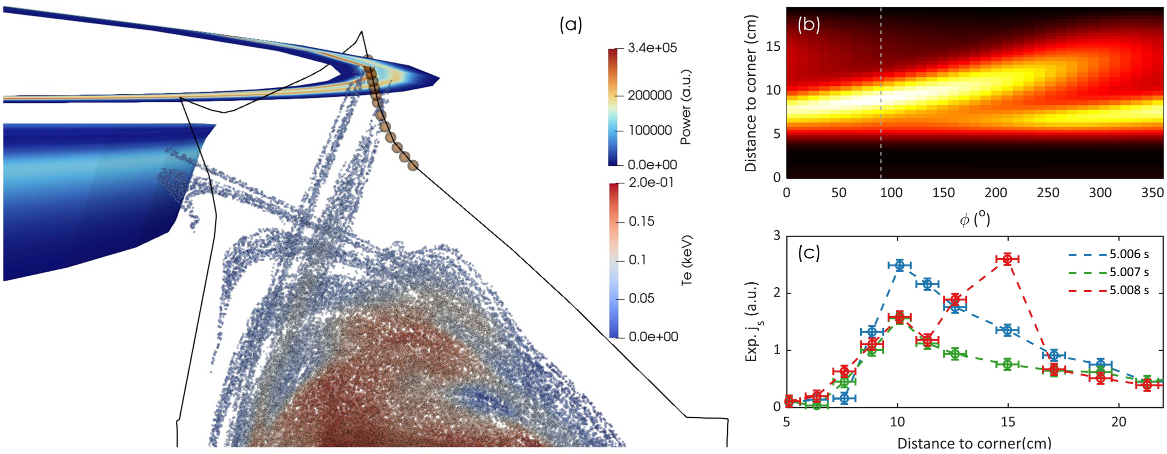

FIG. 2. (a) Poincaré plot of the magnetic topology and the resulted strike point splitting on the divertor; (b) 3D parallel convective particle flux orthogonal to the upper-outer target. The dashed line indicates the toroidal position measured in the experiment; (c) saturated ion flux obtained by the array of Langmuir probes on the upper-out divertor.

Strike point splitting on the divertor during the TQ has been detected by the array of Langmuir probes, shown in Fig. 2(c). After impurity injection, the saturated ion flux (j_s) at 5.007 s is initially measured to decrease, which may be attributed to a reduction in parallel fluid velocity caused by the injected cold gas. Then, a clear splitting of strike point has been found during the TQ (5.008 s), and j_s on the second strike point is even larger than the original strike point. This observation could be understood by 3D effects of MHD activities during the TQ. The JOREK simulation presents that MHD modes change magnetic topology and result in strike point splitting near the upper X-point, shown in Fig. 2(a). The bifurcation occurrence of strike point strongly relates to the mode amplitude. The unstable manifolds form two large lobes near the upper-outer divertor, which intersect the divertor target and split the strike point into double stripes. Fig. 2(b) demonstrates that the simulated parallel convective particle flux at the upper-outer target, combined with the strike-point splitting, exhibits an n = 1structure. The simulation results for the upper-outer target consists well with experimental observations, showing the impact of double lobes on local particle transport. This result provides an explanation for the broadening of energy deposition width during the TQ in ASDEX Upgrade [4] and JET.

In summary, TQ dynamics in MGI triggered disruptions have been experimentally demonstrated on EAST and also performed using the JOREK simulation. Impurity injection causes localized pressure perturbation, then induces the radial electric field and MHD instabilities, and finally drives the enhanced impurity influx and strike point splitting of heat flux. These findings provide valuable guidance for future ITER experiments on disruption mitigation.

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