Study of the Locked Mode Disruption with the 3D Imaging Data in KSTAR

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Abstract. The stimulated minor disruption has been studied in the KSTAR NBI heated L-mode discharge. The minor disruption can be divided into four phases in terms of the T_e profile change. Possible mechanisms for the phase transition are suggested based on the magnetic and T_e fluctuation measurements. In particular, it is found that the role of the T_e turbulence can be important for the T_e collapse of the minor disruption.

1. Introduction

The resonant magnetic perturbation (RMP) field in the tokamak plasma has been widely used for many purposes [1]; however, a deeper penetration of the RMP field can be of concern. The disruption driven by the RMP induced locked mode is called a stimulated disruption [2], and previous studies have revealed many important results on thresholds of the field penetration and disruption or the thermal collapse dynamics. However, the trigger mechanism of the disruption is still largely unknown. In this experiment, a minor (partial) disruption process has been studied using the T_e profile as well as magnetic and T_e fluctuation measurement. It was found that the local T_e gradient and turbulence amplitude between the core and the q=2 region are important for the onset of the fast global T_e collapse in the minor disruption.

The paper is organized as follows. In Section 2, multiple phases of the minor disruption will be identified based on T_e profile change. The possible phase transition mechanisms will be discussed with the magnetic and T_e fluctuation measurements in Section 3. A brief summary and remarks will be given in Section 4.

2. Phases of the stimulated minor disruption

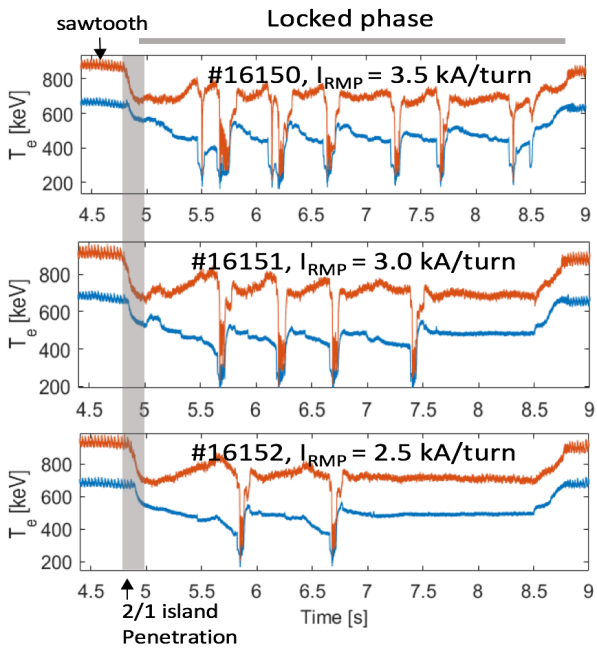

FIG. 1. T_e time traces of the 2/1 island during the locked phase of the KSTAR L-mode discharges. Multiple stimulated minor disruptions are observed.

The n=1 resonant magnetic perturbation (RMP) was applied to the co-I_p neutral beam injection (NBI) heated L-mode discharges to study the stability of the externally driven locked mode on the Korea superconducting tokamak advanced research (KSTAR) device. The RMP coil current was turned on at t = 4.5 s, reached the flat-top at t = 5 s, and was turned off at t = 8.5 s in all discharges. The flat-top coil current was changed shot-by-shot (see FIG. 1). Note that supersonic molecular beam injection (SMBI) was performed four times (t = 5.5, 6.0, 6.5, 7.0 s), though the perturbation due to SMBI was irrelevant to the locked mode stability.

In all discharges, the flat-top RMP field was sufficient for deep penetration of the field. When the RMP field was penetrated deeply into the q=2 region and the stationary m/n=2/1 magnetic island was formed as shown in the FIG. 2, and the stimulated minor (partial) disruptions [2] were observed *repeatedly* as shown in FIG. 1.

The red and blue T_e time traces in FIG. 1 are from the 1D electron cyclotron emission (ECE) channels located in $r < r_s - W/2$ (beyond the inner island separatrix) and $r_s - W/2 < r < r_s + W/2$ (within the island separatrix), respectively, where r_s is the 2/1 island position and W is the island full width. The difference between these two time traces corresponds to the local T_e gradient near the q=2 region. The increase of the gradient before the minor disruption implies that the T_e profile is closely related to the onset of the minor disruption.

The T_e profile analysis during a single minor disruption period finds four distinguishable phases (1—4) and clearly demonstrates the importance of the local T_e gradient in the minor disruption. For an example, the T_e profiles for t = 6.3—6.7 s in #16151 are shown in FIG. 3. The phase 1 is the quasi-steady state with the 2/1 magnetic island. In the phase 2, the T_e gradient between the core and the q=2 region increases in time slowly. Then, the overall T_e drop is observed from the phase 2 to the phase 3. The drop of the edge region ($r > r_s$) is much more pronounced than the core region, which makes a large jump in the T_e gradient. A large T_e global collapse follows rapidly, and the phase 4 corresponds to the time right after the collapse. Note that the 2D T_e profiles in FIG. 3(b) are reconstructed through the cross-

calibration of the electron cyclotron emission imaging (ECEI) diagnostic data against the 1D absolutely calibrated ECE diagnostic.

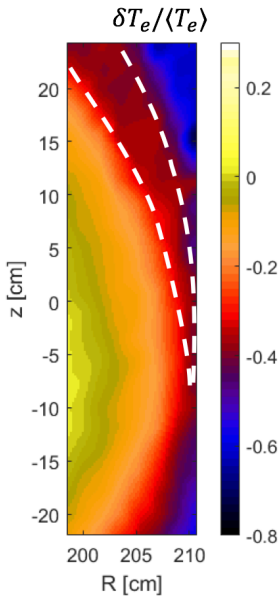

FIG. 2. The 2D relative electron temperature change in the post-penetration phase against the pre-penetration phase is shown. The localized T_e drop within the white dashed line is an indication of the 2/1 magnetic island (the n=1 Mirnov coil fluctuation arises after the unlocking). The X-point seems to be located below the midplane, which is determined by the phase of the RMP field and fixed in the experiment.

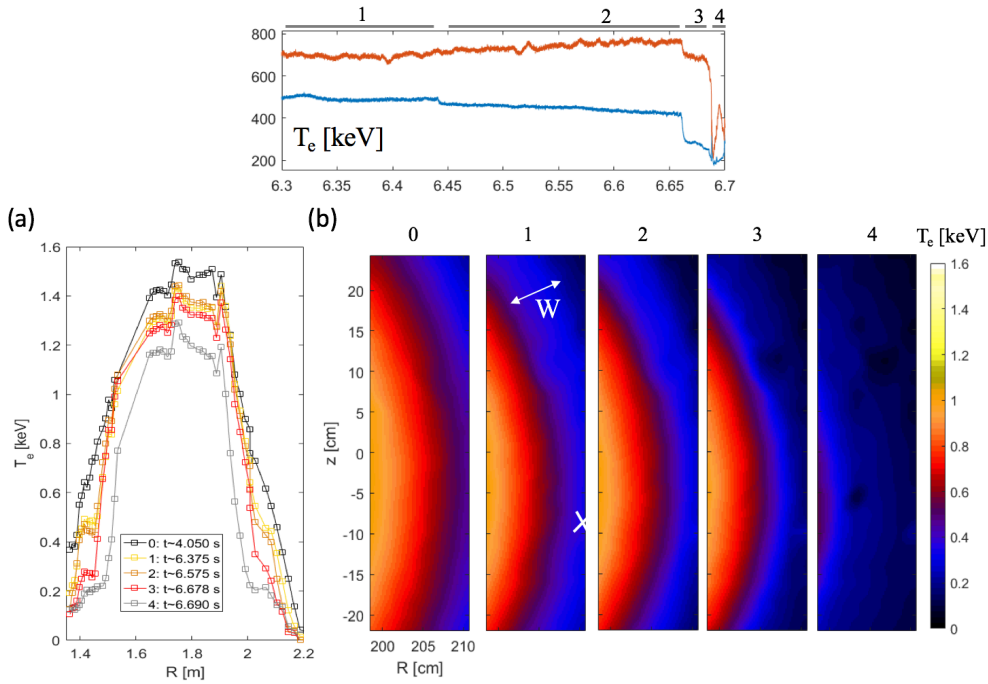

FIG. 3. (a) The midplane T_e profiles measured by the 1D ECE diagnostic find four different phases in a single minor disruption. The phase 0 is before the RMP turned-on. The phases 1—3 are before the fast global T_e collapse, and the flat regions near R~1.43 m and R~2.08 m correspond to the 2/1 island. The phase 4 is after the collapse. (b) The 2D T_e profiles obtained in the low field side are shown for each phase. The light blue in the phase 1 indicates the island region. The T_e gradient increases due to a large decrease of T_e near the q=2 region for 1→3.

3. The fluctuation measurements and the phase transition mechanism

As discussed in the previous section, the phase transitions of 1→2→3 are related to the local T_e gradient increase largely by the edge region ($r \geq r_s$) transport increase. The mechanism for the increased edge transport is unknown, but the high (~20 kHz) frequency magnetic fluctuation (HMF) measured by the Mirnov coil may provide a hint for the phase transition 1→2.

FIG. 4 shows the Mirnov coil spectrogram estimated by the discrete Fourier transform. The HMF appears right after the RMP turn-on time when the RMP field is not deeply penetrated yet. It is clearly distinguished from the 2/1 island fluctuation just after the unlocking measured by both the Mirnov coil and ECE diagnostic. The HMF was not detected by any ECE channel. It implies that the HMF may involve an undetectably small T_e fluctuation or exist on the edge region ($r_s + \frac{W}{2} < r < a$) where the ECE diagnostic may not have sufficient resolution.

The HMF is observed only for the phase 1 and disappears as the phase moves from 1 to 2. One possible scenario is that the HMF mode on the edge region interacts more with both the stationary 2/1 island and the RMP field and becomes locked. The edge mode growth and locking can trigger the phase transition from 1 to 2.

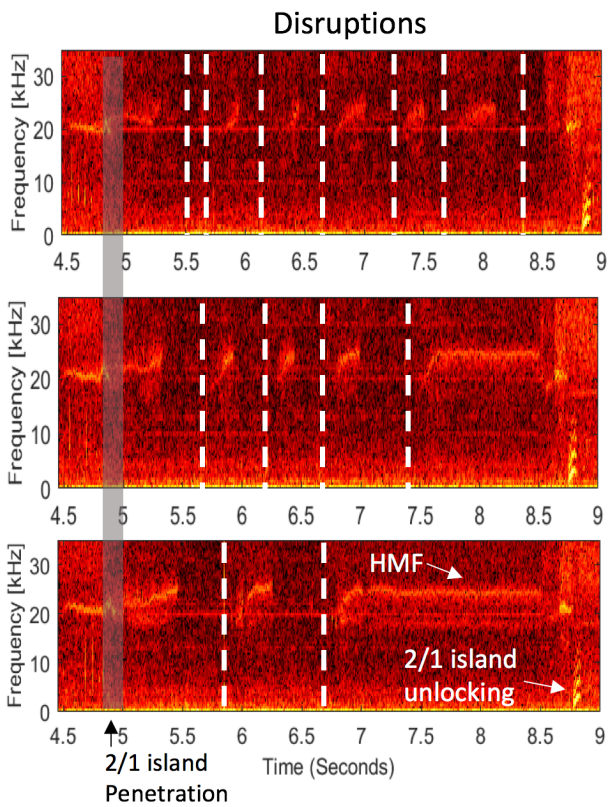

FIG. 4. The high frequency magnetic fluctuation (HMF) measured by the Mirnov coil diagnostic. The white dashed line indicates the fast global collapse (3→4) of the minor disruption. The 2/1 island signal arises after the unlocking.

In the phase 2, the edge transport increase was slow but steady. The mechanism for the phase transition 2→3 may be associated with the RMP field strength. In fact, the phase 3 is very short (~20 ms) and almost same in all discharges, but the period of the phase 2 is clearly correlated with the RMP field strength and determines the disruption frequency. The stronger RMP field results in more frequent disruptions.

The Hender's empirical law [2] for the stimulated disruption threshold, i.e. the disruption occurs when $W/(r_s - a)$ reaches some critical value where W is the island width, r_s is the radius

of the mode rational surface, and a is the minor radius, may help to understand this correlation. First, the 2/1 island sizes in the phase 2 in three discharges were compared from the 1D midplane T_e profile, but they are already saturated with a similar value within the measurement error.

However, note that the effect of the RMP field is not limited to the resonant rational surface. Especially, the edge profile change (T_e drop) by the magnetic perturbation is often observed [3]. The increased RMP field is correlated with the increased edge transport, hence the fast removal of the edge pressure. In turn, this decreases the minor radius and leads to the phase transition 2→3.

In the phase 3, the T_e drop near the q=2 region is significant and the T_e gradient between the core and q=2 region increases significantly. This phase cannot survive for a long time, and an explosive T_e collapse follows, i.e. the phase transition 3→4.

To understand this T_e gradient-driven collapse, the T_e turbulent fluctuation level is studied using the ECEI diagnostic. First, the cross power spectral density (CPSD) is calculated from the discrete Fourier transforms of two vertically adjacent ECEI channels. The result shows a significant fluctuation over the 5—90 kHz frequency range. The CPSD is integrated over the 5—90 kHz frequency range to see the time evolution of the root-mean-square T_e turbulence amplitude. The bottom graph in FIG. 5(a) shows the result. The T_e turbulence increases slowly and becomes saturated for the phase 2 with the local T_e gradient change, but goes beyond the saturation level in the phase 3. The fast T_e collapse can be relevant to the interaction between the magnetic island and the increased T_e turbulence.

FIG. 5(b) illustrates the 2D T_e turbulence amplitude image in the phase 3, using all available vertical pairs of the ECEI diagnostic. The significant turbulence is only measured near the steep T_e region slightly above the expected X-point of the 2/1 island. This poloidal asymmetry is consistent with the numerical simulation in [4].

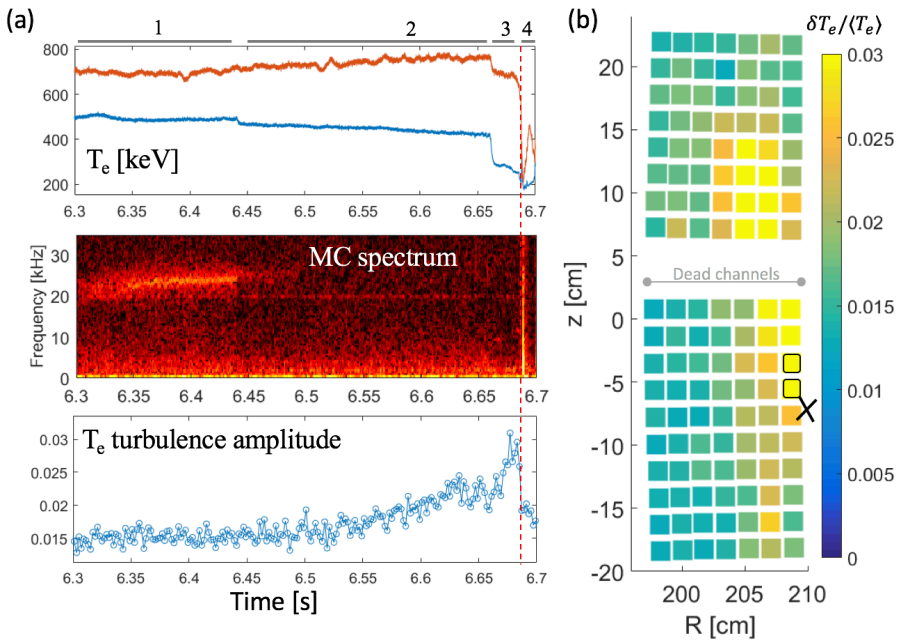

FIG. 5. (a) The time evolution of the T_e turbulence is calculated from two ECEI channels whose positions are marked in (b) as black rectangles. (b) The T_e turbulence amplitude image. Each value is obtained from the channel at that position and the one below. One row of the ECEI channels was dead in the experiment and not shown.

4. Summary and remarks

The stimulated minor disruption has been studied in the KSTAR NBI heated L-mode discharge. The period of the minor disruption can be divided in four phases (1—4) in terms of the T_e profile. The possible mechanisms for the phase transition 1→2, 2→3, and 3→4 are suggested based on the magnetic and T_e fluctuation measurements. In particular, for the fast global T_e collapse, the T_e turbulence can play an important role.

In spite of these studies, there remain many unanswered questions. For example, how can the steep T_e profile be maintained between the core and the q=2 region? In this experiment, the 2/1 island behaves like an internal transport barrier. In fact, another similar experiment showed that the strong flow shear can develop across the 2/1 island X-point [5], possibly due to the asymmetric radial electric field perturbation of the island [6]. In addition, the T_e turbulence measurable with the ECEI diagnostic is only the low-k ($k_\perp \rho_i \leq 1$) turbulence. The time evolution of the high-k turbulence will be interesting.

Besides the T_e profile, the density and/or current profile may be also important for the stability of the locked mode. However, these were not available with sufficient time resolution in this experiment.

Although the experiment is done in the L-mode discharge with the low NBI power, similar characteristics, e.g. the HMF, are also observed in the RMP stimulated minor disruptions of the high NBI power H-mode discharge experiments. Note that the frequency of the HMF is much higher in the high NBI power case.

As a final remark for the application on the disruption avoidance, the HMF or the T_e turbulence amplitude can be used as precursor of the disruption. While T_e may be better in predicting the collapsing time, the 2D nature of the T_e turbulence may require more than one lines of sight.

Reference

[1] EVANS, T.E., "Resonant magnetic perturbations of edge-plasmas in toroidal confinement devices," Plasma Phys. Control. Fusion **57** (2015) 123001.

[2] HENDER, T.C., et al., "Effect of resonant magnetic perturbations on COMPASS-C tokamak discharges," Nucl. Fusion **32** (1992) 2091—2117.

[3] TAMAIN, P., et al., "Edge turbulence and flows in the presence of resonant magnetic perturbations on MAST," Plasma Phys. Control. Fusion **52** (2010) 075017.

[4] WILSON, H.R. and CONNOR, J.W., "The influence of magnetic islands on drift mode stability in magnetized plasma," Plasma Phys. Control. Fusion **51** (2009) 115007.

[5] CHOI, M.J., et al., The 6th Asia Pacific Transport Working Group International Conference, Korea University, Seoul, Korea (2016)

[6] IDA, K., et al., "Radial electric field and transport near the rational surface and the magnetic island in LHD," Nucl. Fusion **44** (2004) 290—295.