DISRUPTIONS AND MHD INSTABILITIES OBSERVED IN THE INITIAL OPERATION PHASE OF JT-60SA

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Characteristics of disruptions in the initial operation phase of JT-60SA, the largest superconducting tokamak in the world, have been identified. These disruptions have been classified into three categories: 1) vertical displacement events (VDEs), 2) control-failure disruptions, and 3) radiative disruptions, and the characteristics of disruptions have been discussed for each category. Plasma elongation achieved before VDEs was in good agreement with that predicted by the nonlinear MHD equilibrium control simulator (MECS) [1], which indicates the MECS can predict the VDE well. Moreover, MHD instabilities observed in this phase have been discussed, particularly the off-axis sawtooth-like crashes with precursory n=1 magnetic perturbation, which persisted for hundreds of milliseconds and obstructed the plasma current ramp-up at low-B_t. The above analysis can contribute to reducing disruptions and MHD instabilities in the next operations of JT-60SA and the initial operations in ITER and other future tokamaks.

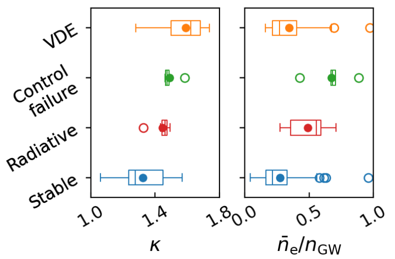

Figure 1. Distributions of κ and $\bar{n}_e/n_{GW}$ for each disruption category and stable discharges.

Investigating the disruptions observed in the initial operation of large tokamaks like JT-60SA can contribute to identifying disruptions likely to occur in the early operations of future tokamak devices like ITER. In total 82 discharges disrupted out of 151 discharges in which the plasma shape and position were under control in the initial operation phase of JT-60SA (here disruptions without feedback control are not counted). These 82 disruptions have been categorized into three classes according to their characteristics [2]. According to the parameter regions for these three categories and stable discharges shown in Fig. 1, the VDEs were likely to occur in high-κ region and control failure disruptions were observed in higher density region than other disruptions.

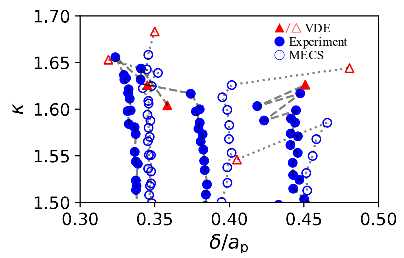

Figure 2. Comparison between κ-scan experiment (closed dots) and MECS simulations (open dots) regarding the relationship between κ and averaged gap between plasma and vacuum vessel wall δ normalized by minor radius a_p.

The first category is VDEs. In large superconducting tokamaks, the predictability of VDEs is essential because the coil inductance is high and the number of coils is limited compared to conventional conducting tokamaks. It was expected that the VDEs would be the main cause of disruptions since the stabilization plate was not yet installed in this phase, and indeed, 58 VDEs were observed, the most among the three categories. By comparing VDE and non-disruptive discharges, it was revealed that the VDEs were likely to occur when κ was high and the gap δ between the plasma surface and the vacuum vessel was large. The trajectories of κ in κ-scan experiments and simulations with the MECS with different gaps are shown in Fig. 2. The κ reached before the VDE occurred increased as the normalized gap δ/a_p gets smaller, where a_p is the minor radius. The MECS simulation well reproduced the relationship between δ/a_p and achieved κ. This result suggests that the pre-experiment MECS simulation is useful to identify the VDE-free operational region for future operations.

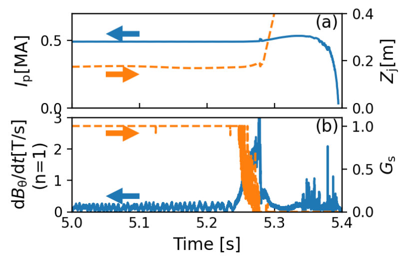

Figure 3. Typical waveforms of (a) I_p and Z_j and (b) $n = 1$ magnetic perturbation amplitude and G_s for control failure disruption.

Disruptions in the second category were caused by the failure of the control scheme due to the non-toroidally symmetric magnetic mode. As shown in Fig. 3, when the $n = 1$ magnetic perturbation grew, the controllability of the plasma shape and position was lost, which is shown in the decrease in G_s, leading to the rapid vertical movement of plasma. Here, G_s is the indicator of the coil voltage availability for the plasma shape and position control. The $n = 1$ mode was thought to be the tearing mode with poloidal mode number m of two with the resonance surface around $\rho = 0.45$, according to the magnetic probe signal and the phase inversion of the soft-X ray (SX) perturbation, respectively. Although it is known that the tearing mode is the major cause of JET disruptions [3], this $n = 1$ mode was not regarded as the direct cause of these disruptions because the control failure terminated the discharges while the mode was growing. In the next operation phase, the signals of the magnetic sensors located at multiple toroidal positions will be averaged to ignore non-axisymmetric perturbations in the plasma shape and position control, thus this type of disruption could be avoided. This is the technical lesson useful for developing future tokamak plasma control.

The last category, radiative disruptions, is characterized by slow current decay with multiple spikes in the SX signals and plasma current, which can be seen in Fig. 4 (a). These disruptions are thought to be triggered by an imbalance of heating power and radiative loss at the plasma edge because they occurred just after the ECH stopped and/or in high particle supply conditions. As shown in Fig. 4 (b), the spikes in the SX signal had inverted directions between the core and edge channels, and the inverse position (channel) was moving toward the core. At the same time as the spikes, n=1 magnetic perturbations grew and crashed. These facts imply that the cooling front was penetrating while slow current decay, and the spikes occurred when the cooling front crossed the resonance surface.

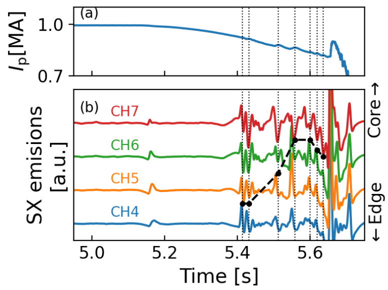

Figure 4. Typical waveforms of (a) I_p and (b) 10–100 Hz bandpass filtered line integrated SX emissions for radiative disruption. The dashed vertical lines represent the timing of I_p spikes and the black-dashed line in (b) indicated the SX spike reversal positions.

The non-disruptive MHD instabilities observed in this phase have also been investigated. In the plasma start-up experiment in low-B_t of 1.7 T, the sawtooth-like oscillations in line-integrated SX emissions were observed and the plasma current ramp-up was disturbed simultaneously. Note that the ECH resonance layer was off-axis due to the low-B_t in this experiment. The lines of sight of the SX detector array are shown in Fig. 5 (a). The phase of the sawtooth-like crashes in the SX emission was inverted near the plasma edge, as shown in Fig. 5 (b). A reduction of the electron temperature T_e before and after the crash was small in the core region but was significant near the edge, which is similar to the MHD instabilities known as the off-axis sawtooth or annular crash [4, 5]. Before each off-axis sawtooth-like crash, the SX emission oscillations of about 1 kHz were observed and the phase of this precursor inverted twice near the edge. The precursor perturbation might be the double-tearing mode which is known as the cause of the off-axis sawtooth.

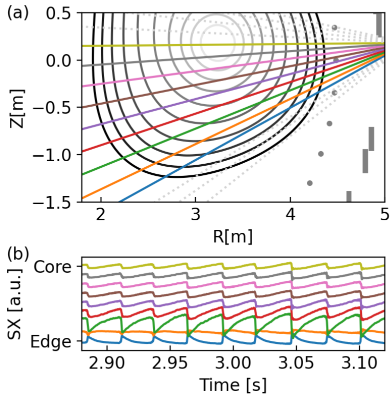

Figure 5. (a) Lines of sight of SX detector array on the contour of poloidal flux, (b) 10‑1000 Hz band pass filtered soft X-ray emissions with off-axis sawtooth-like crashes.

The conditions where the disruptions are likely to occur in the initial operation of the large tokamak have been summarized. It has been confirmed that the pre-experiment simulation is useful in predicting the occurrence of VDEs. Moreover, it is important to eliminate the effect of non-axisymmetric magnetic perturbations for stable control of plasma shape and position. Identification of the MHD instability during the current ramp-up as an off-axis sawtooth can contribute to developing a stable plasma start-up scenario in low-B_t.

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