Integrated disruption avoidance and mitigation in KSTAR

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The final target of Korea Superconducting Tokamak Advanced Research (KSTAR) aims advanced tokamak operation at plasma current 2 MA and toroidal field 3.5 T [1]. In order to safely achieve the target, disruption counter-measures are unavoidable when considering the disruption risks, inevitably accompanied with high performance discharges, such as electro-magnetic load on conducting structures, collisional damage by run-away electrons, and thermal load on plasma facing components (PFCs) [2]. In this reason, the establishment of integrated disruption mitigation system (DMS) has been started for routine mega-ampere class operations of KSTAR since 2013 campaign. The DMS mainly consists of the disruption prediction and its avoidance/mitigation in company with logical/technical integration of them. We present the details of KSTAR DMS and the related experimental results in this article.

1. Introduction

The responses against plasma disruption can be divided in two categories. First one is active avoidance of plasma disruption. Various techniques of the active avoidance have been demonstrated, for instance, electron cyclotron heating (ECH) against density limit disruption. In a broad sense, almost all MHD feedback stabilizations could be included in the active avoidance of plasma disruption such as the magnetic feedback stabilization of resistive wall mode (RWM) and the suppression of neoclassical tearing mode (NTM) by auxiliary current drive.

Second one is so called disruption mitigation. Massive gas injection (MGI) for safe termination of discharge has been studied intensively so far in many devices. MGI mitigation presented promising results against the mentioned disruption risks. However, there are expectations that MGI is not sufficient for the disruption mitigation in reactor scale devices. Thus other mitigation techniques such as shattered pellet injection are studied as well for securing the safety of ITER further.

The above-mentioned techniques require certain response time in reaching satisfactory mitigation level. The response time is governed by both the time scale of plasma phenomena and the reaction time of mitigation hardware. As a result, *early warning*, which guarantees enough response time, becomes a crucial factor in *integrated* disruption avoidance and mitigation. *Early warning* necessitates careful treatments of disruption precursors which are usually originated from disruption-causing instability.

In this article, section 2 describes the disruption prediction in real-time manner. Section 3 depicts the counter-measures against the disruptions. Then section 4 summarizes the mentioned results and discusses possible improvements.

2. Real-time disruption prediction

2.1. Axisymmetric signals and global parameters

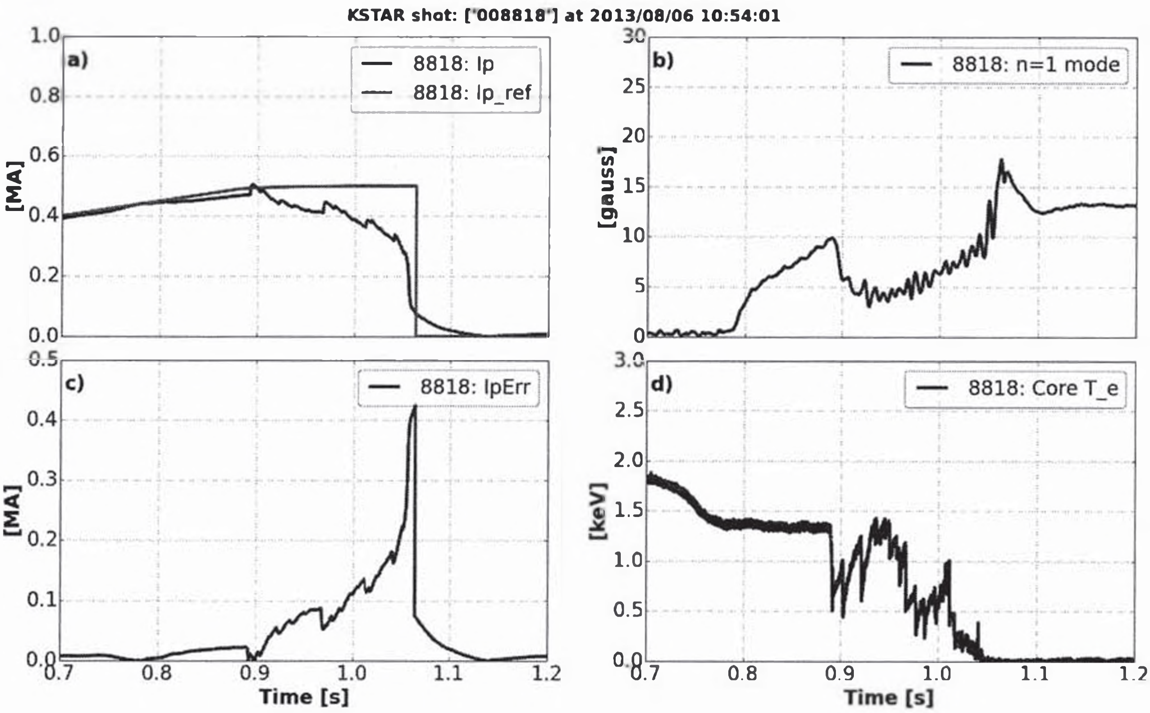

Fig. 1. Detection of locked mode. a) Plasma current. b) Locked mode amplitude. c) Discrepancy between measured plasma current and its feedback target. d) Core electron temperature.

In 2013 KSTAR campaign, we used namely I_p error that is the discrepancy between measured (*i.e.* actual) and feedback target of plasma current as a major disruption precursor. As shown in figure 1, the plasma current became deviated from the target despites of the feedback action when strong locked mode took place. The notable points of figure 1 are different time behaviors among the precursor signals. The amplitude of locked mode depicted starts to grow from t=0.788 s. However, minor disruption at t=0.895 s makes the prediction difficult since the mode amplitude decreases temporally right after the minor disruption and increases again during 150 ms period. On the contrary, I_p error exhibits a steady increase during the period. In the same period, core electron temperature shows sudden drop and slow recovery.

From the observations in figure 1, it can be concluded that we might fail in the prediction and the early warning of disruptions if we solely rely on the mode amplitude that directly causes the disruption. We could recognize the real situation when the global parameters are also taken into account.

KSTAR plasmas typically have highly elongated shapes (*i.e.* elongation κ~2) for pursuing advanced tokamak operations in high beta where beta is the ratio between thermal and magnetic pressures. In this reason, KSTAR discharges are inherently vulnerable to VDE and the largest portion of plasma disruptions in KSTAR has been caused by VDE so far.

In VDE, plasma vertical position Z_P and its time derivative dZ_P/dt correspond to the mode amplitude and the mode growth, respectively. Therefore, the integrated DMS of KSTAR adopts Z_P and dZ_P/dt as precursors of VDE. However, dZ_P/dt, which is typically derived from the numerical differentiation of Z_P, is susceptible to a noise due to the characteristics of numerical differentiation. In order to moderate the noise problem, the DMS considers the current on in-vessel vertical control coils (IVCCs) as an alternative of dZ_P/dt. In the experiment, the determination of VDE is conducted by the logical combination of them through AND/OR logic with their own thresholds [3].

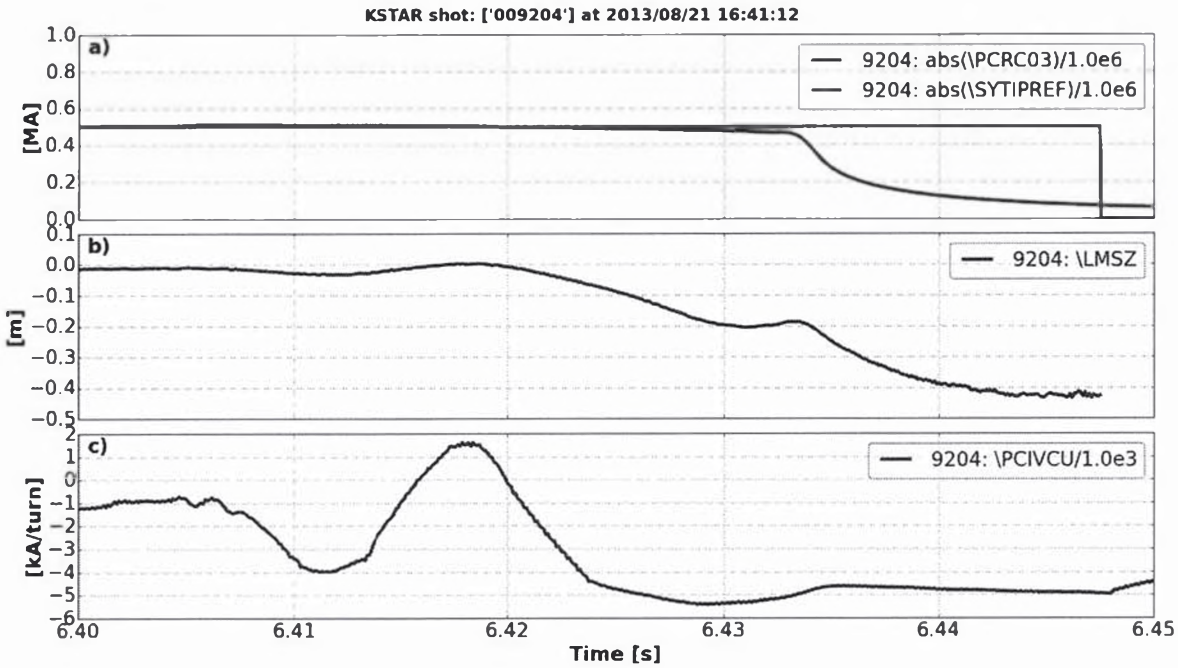

Fig. 2. Typical behaviors of *LMSZ* and *PCIVCU* during the VDE. a) Plasma current (blue line) and its control reference (green line). b) Plasma vertical position. c) Current on IVCC.

2.2. Non-axisymmetric signals

Although locked mode-induced disruptions have not frequently occurred in KSTAR so far, it could be expected that locked mode becomes a serious issue in high performance discharge in conjunction with potential amplification of error field. In 2013 KSTAR campaign, we concentrated on in-situ detection of slowly rotating mode and its integration to the DMS. To detect slowly rotating/non-rotating mode, KSTAR has several picture frame type coils which are sensitive to mode amplitude rather than mode frequency.

Additionally, the real-time prediction of the disruption requires the rejection of equilibrium component in in-situ way. For the purposes, 180° hard-wired pairing configuration was implemented in the picture frame type coils such as locked mode detection coils and saddle loops as depicted in figure 3. The 180° hard-wired pairing configuration is essential for in-situ detection of MHD instability since it inherently rejects n=0 equilibrium component (actually all n=even components) and extracts n=1 instability component (actually all n=odd components). We assume that n=1 mode takes a major portion among all n=odd components [3].

However, we did not utilize the locked mode detector in 2013 experiments because it still needed compensation of pick-ups from poloidal field (PF) coils and even plasma current. The locked mode amplitude depicted in figure 1 is the post processed result and the compensation applied in figure 1 will be implemented in the KSTAR PCS. From next campaign, the KSTAR DMS will be able to take the compensated signal of locked mode in real time.

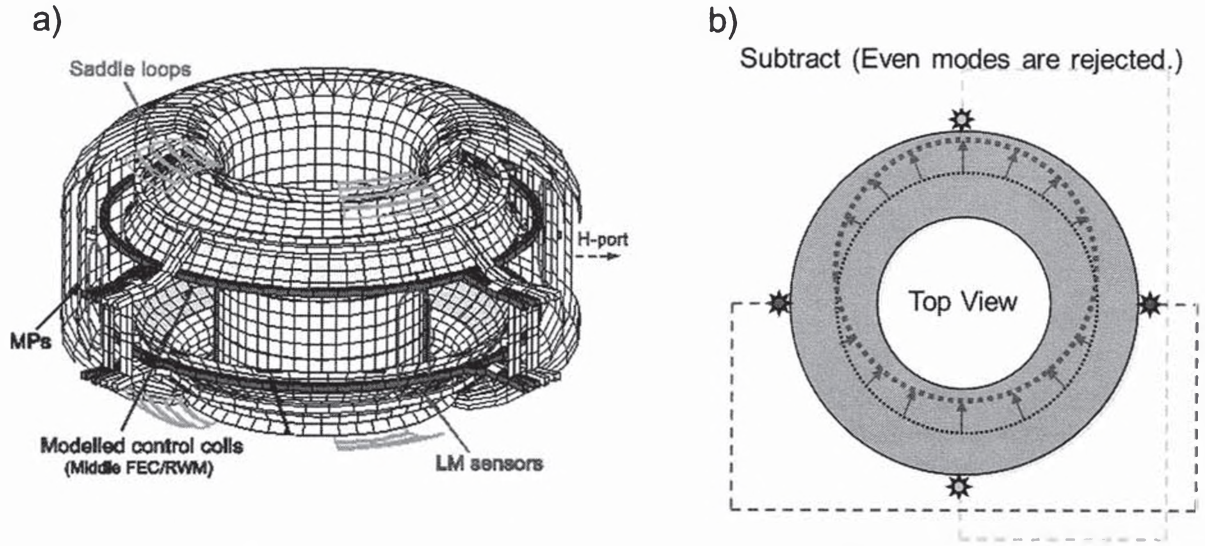

Fig. 3. 180° hard-wired pairing of picture frame type sensors. a) Magnetic sensors installed in KSTAR. b) Schematic view of equilibrium portion rejection.

3. Disruption avoidance and mitigation

3.1. Unplanned ramp-down of plasma current

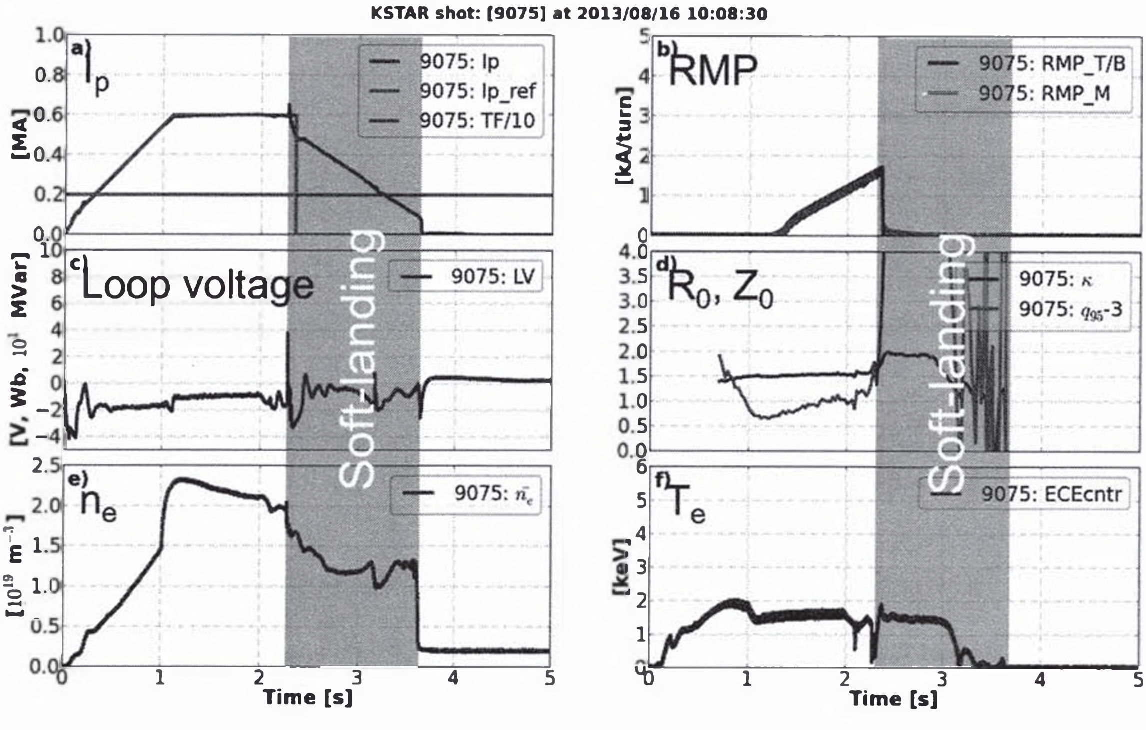

Fig. 4. Asynchronous ramp-down against simulated locked mode. a) Plasma current (blue line) and its control reference (green line). b) Currents of field error correction coils. c) Loop voltage. d) Elongation (blue line) and q_{95} (green line). e) Volume-averaged density. f) Core electron temperature.

In order to realize unplanned I_p ramp-down in KSTAR device, two functions are newly implemented in KSTAR PCS. First function is the reassignment of control targets after the trigger of the unplanned phase. The control targets include not only preprogrammed target of plasma current but also other targets such as desired plasma shape since the unplanned ramp-down phase is almost identical to the planned ramp-down phase after the transition of phase [4].

Second one is the reprogramming of feedback algorithm and feedforward waveform. This consideration is more crucial in superconducting devices because the responses of superconducting PF coils are much slower than those of normal conductor devices. Thus the well-programmed waveforms of feedforward control are inevitable for compromising narrow gain window of feedback control.

Figure 4 depicts the example of unplanned I_p ramp-down against locked mode occurrence. In detail, the DMS caught the rise of I_p error due to the locked mode and invoked the unplanned ramp-down. One thing should be noticed is that the locked mode was intentionally induced with using resonant magnetic perturbation..

3.2. Massive gas injection

The above-mentioned advantages of unplanned ramp-down may act as a handicap when the allowed response time to plasma disruption is not sufficiently long. For instance, superconducting device KSTAR typically has sub MA/s of I_p ramp-rate and it takes almost second in the ramp-down of MA class discharge below the safe level (*e.g.* I_p<500 kA). On the other hand, VDE only permits several *ms* of the response time in order to prevent severe damage.

In this reason, we implemented fast shutdown technique, MGI as well and it was successfully commissioned within integrated DMS.

4. Summary

In order to achieve stable MA class operation and high performance discharges, integrated DMS was implemented and applied during 2013 KSTAR campaign. Under the integrated DMS framework, various diagnostics and actuators were combined and controlled logically for the purposes of real-time disruption prediction and avoidance/mitigation. In future, the DMS will be upgraded to properly respond to diverse disruption causes which have their own time scale (*i.e.* allowable response time). Through the upgrade, we will pursue to increase the probability of disruption mitigation.

Acknowledgement

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