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Implementation of the forced landing scheme under off-normal events in KSTAR

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ABSTRACT

Disruption avoidance is one of the most critical issues in KSTAR due to its high current, temperature and long operation characteristics of the superconducting tokamak. To minimize possible damages to the machine, we imposed a real time handling algorithm of off-normal events, named “forced landing” to ramp down the plasma with well-controlled plasma current and position. Two different plasma control schemes are implemented for different purposes and situations. Both schemes have been successfully demonstrated with careful classifications of actions on the machine in real experiments and they show routine performance with effective reduction of impacts on the machine. Such “machine-protection” schemes enable more aggressive operations such as mega-ampere or high beta experiment, resulting in an expansion of the KSTAR operation regime due to reduced less concerns regarding mechanical safety issues.

1. Introduction

As the plasma current and stored thermal energy increase in recent tokamaks, plasma disruption becomes a critical problem, especially in large scale devices such as international thermonuclear experimental reactor (ITER). The electro-magnetic loads on conducting structures become severe during the high current disruption [1]. Furthermore, disruptions can cause damages to the first wall by excessive thermal load and direct collision of run-away electrons [2]. Consequently, such research on disruptions and their mitigation is necessary for the optimized design of future burning fusion devices.

The cause of the disruptions can be categorized into two major groups [3]. One is related to the plasma's proximity to the MHD stability limit [4]. Plasma control system (PCS) in KSTAR has the a real-time monitoring function for the detection of disruption precursors that could potentially develop into a major disruption [5,6]. The other group of disruptions is due to loss of essential control that originates from the failure of hardware. Occasionally during a discharge, it occurs that actual control parameters (e.g. plasma current) deviate significantly from the target value and eventually PCS loses its control. Faulty diagnostics or an abrupt change of plasma state can cause subsequent failure of the plasma control. Usually this type of hardware failure event is triggered by the plant monitoring system and relayed to the PCS to activate possible fault protection algorithm [6].

When the magnitude of the disruption precursor exceeds the predefined limit or the PCS receives a hardware fault signal, the PCS enters a new state of disruption avoidance referred to as “forced landing”. The newly implemented scheme of forced landing scenario aims to this avoidance of plasma disruption. The following four actions are taken during the forced landing state. (i) Gas puff and pellets are disabled, (ii) all the heating device are turned off except neutral beam injection (NBI), (iii) a new plasma current target is provided to ramp down the plasma current, and (iv) the plasma is moved inward through simple, minimal boundary flux surface controls.

This technique has several advantages. Firstly, it enables reduction of the plasma stored energy of the plasma by ramping down the plasma current and decreasing the potential to the wall damage. Secondly, the plasma column is secured through maintaining the distance between inboard limiter and inner last closed flux surface (LCFS) until plasma current and stored energy is reduced to safe level. Thus, the hot plasma is prevented from touching outboard plasma facing components (PFC) and important in-vessel structures such as diagnostics and heating devices.

In the next section, the off-normal events that triggers forced landing are defined and categorized with key parameters being taken into account. In Section 3, the strategy of the proposed forced landing is described in detail together with experimental demonstration. Finally, there is a brief conclusion discussing the beneficial usage of the forced

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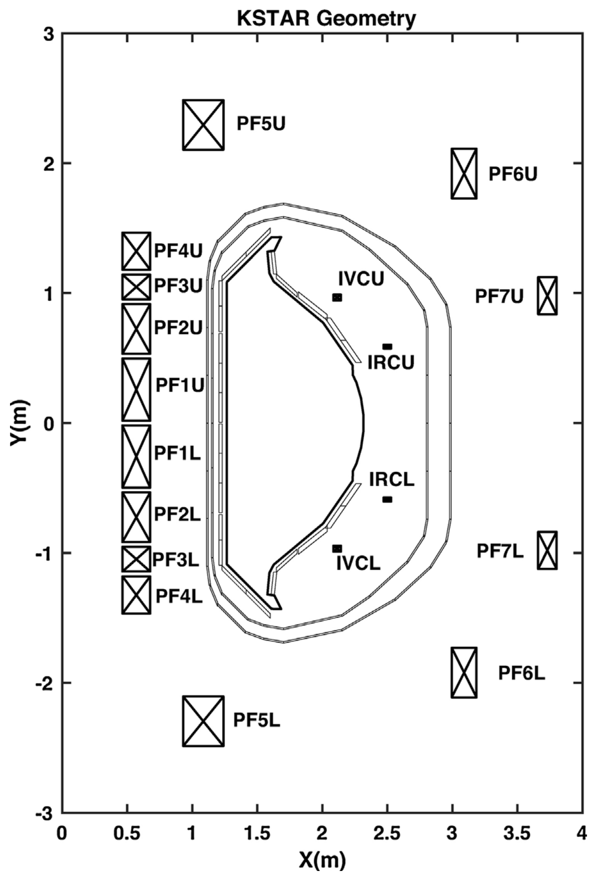

Fig. 1. KSTAR Geometry in 2015 Campaign. 14 poloidal field (PF) coils are installed outside vaccum-vessel structure. Also there are four in-vessel coils where IVCU/IVCL gives vertical plasma control and IRCU/IRCL gives radial plasma control.

landing in KSTAR.

2. Categorization of the off-normal event and key parameters

There are several off-normal events during the plasma discharge that can possibly cause a disruption of the plasma. The proper action to such off-normal events can be classified by the time scale from the onset of the off-normal event to the actual plasma disruption. The response time of the PF coils to the PCS command and plasma current provides the reference time scale that in which the plasma can be ramped down with good controls. In KSTAR, this plasma current control response time is typically about 15–20 ms. Due to the super-conducting nature of the KSTAR PF coils as well as vacuum vessel structure, the PF coils are installed relatively far away from the plasma boundary with huge cryogenic structures in between as shown in Fig. 1 [7]. This means that a forced landing cannot be successfully completed for any events that lead to disruption in less than 20 ms.

The cause of off-normal events can be classified into two categories. First is the loss of control due to limitations or sudden failure of some hardware system in tokamak, which can be identified as an “engineering issue”. The second category contains “physics issues”, usually due to plasma instabilities that can grow as the plasma parameters go near stability boundaries.

The appropriate action for the off-normal events triggered by engineering issue is the “full-feedback scheme”. Whether a forced landing can be applied or not for given off-normal events is determined by which component stops functioning. As shown in Fig. 1, failure of any coil system, such as poloidal field (PF) coil [7] malfunction or in-vessel vertical control coil (IVC) [8] power supply failure leads to an immediate shutdown of the discharge since the magnetic axisymmetric control of the KSTAR is designed to use all the equipped PF/in-vessel coils and practically impossible to design working controls even when one of the actuators is not working. Non-magnetic method such as killer pellets or massive gas injection (MGI) might help to reduce the potential for damages by halo current or runaways [9]. On the other hand, if the coil systems are fully operational and another component failure occurred instead (e.g. heating device failure or PFC overheating warning), the forced landing scheme is very useful because there is still a chance to attempt controlled ramp down of the discharge using available magnetic controls. Hence the forced landing scheme can only be used when a tokamak component other than any coil system failed or reached to a predefined limit.

For the “engineering issue” or hardware failure cases, the design of the forced landing is not sensitive to the plasma conditions, because in most cases the plasma has been controlled very well until the event is triggered. For such cases, it is desirable to apply the most reproducible, routine, simple and general plasma control scheme. Such requirements can be met by adopting the full-feedback scheme that will be discussed in Section 3.3.

When off-normal event is triggered by physics issue, “feedforward forced landing” scenario is the most adequate plasma control scheme. For these events, plasma is already in a marginally controllable state and plasma should be ramped down as fast as possible without crossing the stability boundaries. Any perturbations into the plasma in unfavorable way may lead to disruptions. Thus, plasma control scheme should be sensitive to the plasma conditions and several parameters like loop voltage, beta and shape should be tracked to maintain these stability-related parameters within acceptable ranges.

The goal of the forced landing scenario is to abandon the current operation scenario upon detection of an off-normal event trigger and ramp down the plasma current with well controlled plasma boundary. During the forced landing, the plasma can suffer instability and disruptions due to various reasons. To address such possible disruption issues, following parameters must be considered to avoid subsequent disruption during forced landing.

1. Plasma controllability and heating. Immediately after the event trigger, plasma targets may undergo massive and sudden changes depending on previous operating scenario. A simple control scheme that necessitates minor changes on plasma states is preferred. To minimize disturbances to the plasma, main heating device that is operating at the trigger is left on and turned off only after plasma current crosses a threshold value below which the forced landing is considered “successful”.
2. Plasma current ramp down rate. It can be controlled through changes on loop voltage during forced landing.
3. Radial position of the plasma. The radial position also determines the required loop voltage. For the simplicity, using the standard “isoflux” control algorithm with real time equilibrium fit (EFIT) code [10], we only control inner and outer points defined as intersection of $z = 0$ mid plane and last closed flux surface (LCFS) rather than entire plasma shape or plasma center. The plasma may become inner-wall limited or not, but a careful control is still required because plasma may possibly disrupt by a low-q limit $q_{edge} \sim 2$ due to excessive radial compression.
4. The decay index. Elongated plasmas with a large decay index may suffer from vertical instability [11]. Hence it is important to reduce the decay index by making the plasma more circular for stable ramp down.
5. Greenwald density limit [12]. When the plasma density is large, disruption due to excessive radiation loss is another key concern. Thus, it is important to control the plasma density well below the Greenwald density limit while controlling the plasma current.
6. Ideal MHD stability limit. For the operation at low magnetic field and high current, the forced landing scenario should avoid the low-q limit of $q_{edge} \sim 2$ where the plasma may have external kink type