MULTI-SCALE INTERATION NEAR LOCKED MAGNETIC ISLANDS AND RESULTING DISRUPTION DELAY IN KSTAR

[1]J. KIM, [2]G.J. CHOI, [3]M.K. JUNG, [1]J. LEE, [1]J.W. JUHN, [3]Y.S. NA

[1]Korea Institute of Fusion Energy, Daejeon, Republic of Korea
[2]Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea
[3]Seoul National University, Seoul, Republic of Korea

Email: jayhyunkim@kfe.re.kr

Magnetic fusion devices such as tokamaks and stellarators maintain their confinement due to nested flux surfaces formed by precisely controlled magnetic fields. However, plasma instabilities (e.g., MHD instabilities) or external perturbation of magnetic fields (e.g., error fields) can disturb these nested flux surfaces by inducing macro-scale structures such as magnetic islands. In severe cases, such disturbances degrade confinement performance or, if sufficiently intense, lead to plasma disruption, resulting in the complete loss of confinement. The disturbances of nested flux surfaces occur via magnetic reconnection, leading to the formation of stochastic field lines or cold bubbles [1]. While macro-scale physics, such as the formation of magnetic islands, is driven by magnetic reconnection, the reconnection process itself is strongly influenced by micro-scale physics, such as plasma resistivity. Consequently, modifying the magnetic reconnection process through various mechanisms, including multi-scale interactions, can, in turn, impact macro-scale plasma disruptions.

In the KSTAR device, an experiment was conducted where an external n=1 perturbed magnetic field was applied to an NBI-heated L-mode discharge without pre-existing MHD instabilities, forming a locked magnetic island. The gradual increase in the n=1 perturbed field ultimately led to plasma disruption. Here, to quantify the impact of multi-scale interactions on macro-scale disruption, we intentionally induced plasma disruption using the controllable non-axisymmetric field coils installed on KSTAR. When the magnetic island grows large enough to cause locking and disruption, an H-L back transition typically occurs before disruption, causing the actual disruption to take place in the locked L-mode state. To eliminate uncertainties in quantification arising from the uncontrolled changes during the H-L back transition, the target discharge was selected as an L-mode discharge. During this process, as the plasma approached disruption, strong turbulence was observed around the x-point of the locked magnetic island. Prior studies on magnetic fusion plasmas and astrophysical plasmas have reported that turbulence can accelerate magnetic reconnection [2][3].

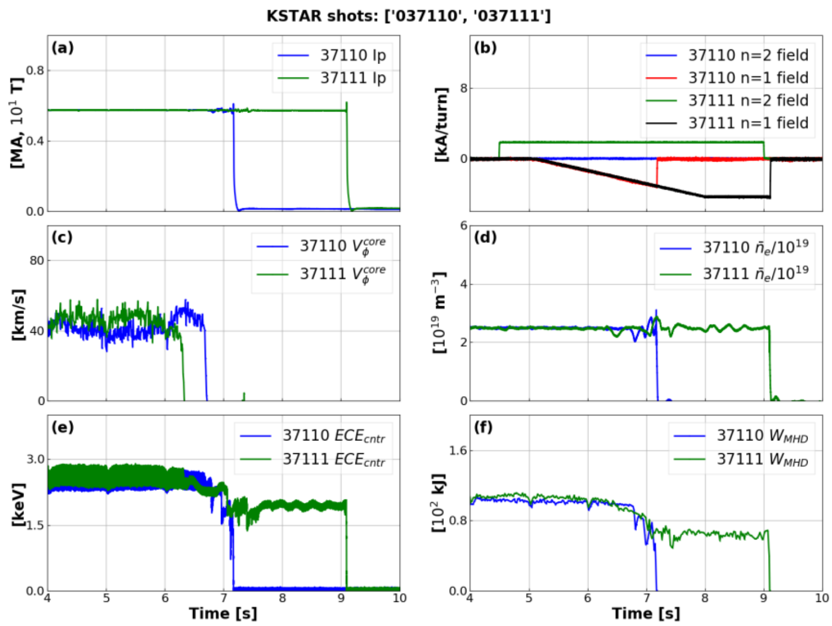

Figure 1 Delay of plasma disruption due to additional n=2 fields: Comparison between shot 37110 (without n=2 fields) and shot 37111 (with n=2 fields). In both shots, the n=1 field is applied in the same manner up to major disruption. (a) Plasma current, (b) non-axisymmetric field coil currents, (c) toroidal rotation, (d) plasma density, (e) electron temperature, and (f) stored energy.

Based on the hypothesis that controlling turbulence to reduce turbulence-driven hyper-resistivity could hinder magnetic reconnection and delay disruption, a comparative experiment was performed as shown in figure 1. In this experiment, an external n=2 perturbed magnetic field was additionally applied to the same discharge to generate poloidal flow around the n=1 locked magnetic island. KSTAR is equipped with non-axisymmetric field coils divided into top, middle, and bottom poloidal sections, all located inside the vacuum vessel. The n=1 field was applied using the middle coils, while the n=2 field was additionally applied using the top and bottom coils. The results showed that, even under conditions where the n=1 perturbed field alone would typically lead to major plasma disruption, the plasma remained away from major disruption with the addition of the n=2 perturbed field. Furthermore, experimental observations indicated that turbulence around the x-point was weakened by the meso-scale poloidal flow [4]. A key distinction to note is that, in conventional discussions of disruption avoidance in magnetic fusion devices, the focus is on preventing disruption by directly controlling the macro-scale disturbances (e.g., MHD instabilities) that cause plasma disruption. In contrast, this study focuses on cases where controlling the disturbance itself is not feasible, making disruption avoidance impossible. Instead, the objective is to regulate the dynamics of the disruption process itself. For example, the additional n=2 perturbed field used as a control knob in this study does not prevent the conventional disruption sequence—shielding of non-axisymmetric fields by plasma rotation → mode locking → disruption. In fact, it accelerates the onset of mode locking through additional neo-classical toroidal viscosity. This study also differs from conventional disruption mitigation approaches. Typically, disruption mitigation—such as massive material injection—aims to control plasma density or impurity levels at the moment of thermal quench, redirecting the energy flow in a safe manner during disruption. In contrast, this study focuses on the dynamics leading up to thermal quench, specifically the stage where magnetic field lines become tangled just before the thermal quench occurs. However, by controlling the process that follows mode locking and leads to a major disruption, this approach could provide additional time to respond to the disruption, thereby enhancing mitigation efficiency.

For a detailed experimental analysis, it is necessary to measure magnetic islands, poloidal flow, and turbulence—which are involved in multi-scale interactions—with sufficient spatiotemporal resolution. Using the electron cyclotron emission imaging (ECEI) system installed on KSTAR, combined with a high-sampling digitizer, various physical phenomena occurring at multiple scales were simultaneously measured. To further understand these observed multi-scale interactions, numerical simulations were performed using the global gyro-kinetic code GENE under conditions similar to the experiment [5]. The simulations confirmed that an n=1 perturbation generated a locked magnetic island and accompanying turbulence near the island, while an additional n=2 perturbation induced poloidal flow around the island, suppressing turbulence. These results reinforce the possibility of multi-scale interactions as observed in the experiment.

This study demonstrates not only the feasibility of controlling plasma disruption dynamics via externally applied macro-scale control knobs but also highlights the intricate influence of micro- and meso-scale physics on macro-scale phenomena. These findings are expected to contribute to the advanced control of plasma disruption and may also provide insights into magnetic reconnection in astrophysical plasmas, where multiple celestial bodies interact.

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