Development of High-performance Long-pulse Scenario and Investigation of Performance Degradation over Long-time Scale in KSTAR

Hyun-Seok Kim[1], YoungMu Jeon[1], Hyunsun Han[1], Kimin Kim[1] and KSTAR Team
[1] Korea Institute of Fusion Energy (KFE)
e-mail (speaker): hskim0618@kfe.re.kr

The primary goal of the KSTAR project is to attain an pulse duration of 300 seconds while achieving a high-performance plasma [1]. To develop long-pulse discharges, the approaches have been directed towards accomplishing objectives: the attainment of an extremely low loop voltage (V_{loop}) and the mitigation of surface temperature increase in the plasma facing components (PFCs). Moreover, dedicated efforts have been undertaken to sustain these desired conditions as long as possible. Since KSTAR primarily employs NBI as the primary H&CD system, the research on fast ion behavior is crucial. In high-performance long-pulse discharges of KSTAR, it was observed that the fast ion behavior was related to the rapid temperature increase in the poloidal limiter and the gradual plasma performance degradation over a long time.

In order to mitigate the temperature increase in the poloidal limiter, based on the analysis of fast ion orbit loss[2], R_{out} of plasma shape was optimized and appropriate NBI sources were selected. Besides, the selection of an NBI source also reduced temperature increase in other PFC such as the inboard limiter. The temperature increase in the central divertor or the outer divertor was mitigated by adjusting the position of the striking point over time. The optimization of the H&CD injection scenario, especially ECH, was important for achieving and sustaining lower V_{loop} with high-performance plasma. One or two ECH injections enabled lower V_{loop} operation for the longer pulse discharge by enhancing the NBI-driven current through the T_e increase. The controlled injection of ECH helped access the high β_P state by improving the fast ion confinement with stabilization of the Toroidal Alfvénic Eigenmodes (TAEs) [3,4]. The higher fast ion confinement in the high β_P state contributed to the mitigation of PFCs temperature increase as well as the improved plasma performance. In addition, KSTAR experienced nonlinear signal drift in the magnetic probes in the long-pulse discharges. The nonlinear signal drift in a discharge impacted on accuracy and reliability of EFIT analysis and led to unintentional errors in the real-time plasma shape control. To effectively resolve this issue, the thermal shielding protector was installed on the magnetic probes, which successfully reduced the nonlinear signal drift.

Based on these efforts, KSTAR has achieved a pulse length of ~90 seconds with high-performance plasma. The KSTAR long-pulse operation conditions were I_P~400 kA, B_T~1.8 or ~2.5 T, P_{NBI}≤5.2 MW, and P_{EC}≤1.4 MW with the optimized plasma shape. The achieved plasma parameters were $\bar{n}_e$ ≤2.8×10^{19} m^{-3}, $T_{e,core}$≤5.0 keV, $T_{i,core}$~2.0 keV, β_P≤2.7, H_{98y2}~1.1, V_{loop}~34-100 mV, and f_{NI}~0.69-0.96 with f_{BS}~0.29-0.37 and f_{CD}~0.40-0.59. However, KSTAR long-pulse discharge has suffered from gradual performance degradation over time. In this work, it was figured out that one of the causes of performance degradation is the degradation of fast ion confinement coupled with relatively weak TAEs. The global analysis through kinetic EFIT confirmed that the thermal stored energy remained almost constant over time, but the fast ion stored energy decreased over a long timescale, resulting in the performance degradation.

Despite attempts to mitigate or suppress the TAEs by utilizing ECH to obtain a high β_P state, the decrease in the fast ion pressure is still thought to be associated with long-lasting TAEs that affected fast ion confinement over a long time. KSTAR high β_P discharges are typically accompanied by enhanced fast ion pressure. This fast ion pressure facilitated the easier activation of TAEs, leading to the degradation in fast ion confinement. Furthermore, in higher βP plasma, as β_P decreased by worsening the fast ion confinement along with TAE activities, the discharge eventually reached a certain level of fast ion pressure, at which point TAEs spontaneously stabilized themselves. Consequently, β_P seemed to be converged to ~2.0-2.2 in the KSTAR long-pulse discharges.

One notable observation is that the intensity of TAEs in the long-pulse discharges was weaker by an order of magnitude than the intensity of TAEs typically observed in KSTAR. The TAEs excited in the long-pulse discharges were not strong enough to degrade the plasma performance during short pulse length, but their cumulative effect on the confinement degradation was evident during long pulse length. The impacts of fast ion confinement can be more significant in ITER, where alpha particle confinement will be crucial for achieving the burning plasma. As demonstrated in KSTAR, the fast ion confinement and associated Alfvénic instabilities should be effectively controlled for successful high-performance long-pulse operation in ITER.

References

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