ON ADVANCED OPERATION SCENARIO DEVELOPMENT IN KSTAR TOWARD COMPACT PILOT DEVICE

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We report on the progress of advanced operation scenario development and its future directions in KSTAR, in preparation for the Compact Pilot Device (CPD) with $R \approx 3.5$ m and $a \approx 1.1$ m, newly proposed as the next-step device in Korea. The scenarios under development can be categorized into two paths: i) those relying on the H-mode edge, including Hybrid mode [1], high-li mode [2], and high-βp mode [3], and ii) those relying mainly on an internal transport barrier (ITB) in the core region, such as limited ITB scenarios [4], FIRE mode [5], and double transport barrier (DTB) mode [6].

Firstly, achievements in fusion performance, steady-state operation, and pulse length are discussed. Fig.1 presents the status of each scenario in terms of fusion triple product and pulse length, including the impact of the divertor material transition from carbon to tungsten. The presence of tungsten impurities introduces significant radiation losses due to core accumulation, which limits fusion performance compared to previous carbon divertor conditions.

Hybrid scenarios have been developed to achieve high fusion performance and steady-state operation. As new approaches, triggering coherent edge-localized modes [7] and transitioning from a lower single-null (LSN) to a double-null configuration [8] have been explored to enhance β_N under carbon divertor conditions. These approaches have been further extended to tungsten-wall conditions as part of the ITPA joint activity and the DIII-D–KSTAR collaborative task force. Newly established hybrid scenarios at $q_{95} \approx 4.5$ and 5.8, are equipped with 3/2 or 4/3 modes as in DIII-D. Furthermore, a long-duration hybrid scenario has been achieved for 35 seconds while maintaining stable plasma performance at $\beta_N \approx 2.5$ as shown in Fig.2(a). Compared to the carbon environment, where gradual degradation of plasma performance was observed, this result demonstrates the feasibility of sustaining a high-performance hybrid scenario in long-pulse operation despite tungsten impurities.

The high-li mode has been pursued to achieve high β_N with a relatively high internal inductance, extending the DIII-D high-l_i steady-state scenario to long-pulse operation on KSTAR. An operation at $\beta_N \approx 3$ has been achieved with $G = \beta_N H_{89}/q_{95}^2 > 0.3$ at $q_{95} < 5$, approaching the fully non-inductive Q = 5 goal for ITER. Stationary high-β_N operation has been extended to ~15 seconds without obvious signs of performance degradation (Fig.2(b)). The high-li mode has been reproduced at $\beta_N \approx 3$ in the upper single null configuration with the lower tungsten divertor, demonstrating robust and reproducible access to the high- β_N regime, relatively insensitive to available NB power mix and wall/machine conditions due to its simple access recipes.

The high-βp mode has been established primarily for long-pulse operations in KSTAR. A pulse length of 100 s has been achieved with $f_{BS} \approx 0.30$–0.35, $f_{NI} \approx 0.75$ –0.77, $H_{98y2} \approx 1.1$, and $ne(0) \approx 3.35\times10^{19}$ m−3. Under a new joint activity between DIII-D and KSTAR, a DIII-D-like high-β_p mode has been attempted under KSTAR constraints, aiming to produce a large-radius ITB in high-density plasmas despite the challenge of limited available heating power and tungsten impurity effects on plasma performance. Although the overall performance was somewhat weaker than in DIII-D, high-density, high-βp discharges with large-radius ITB have been achieved.

The inboard-limited ITB has been investigated in a carbon-wall environment. Early NBI with power > 4 MW under limited L-mode conditions is essential for ITB formation in both ion and electron transport channels. The inboard-limited configuration avoids the H-mode transition, as the L-H power threshold exceeds that required for ITB formation. Additionally, an upshifted plasma shaping to the unfavourable grad-B direction, extends ITB operation by lowering the power threshold, even with marginal NBI power (~3 MW). This approach also aids impurity control and mitigates damage to the inboard limiter, enabling sustained ITB access across various NBI heating conditions. Following the upgrade of the lower tungsten divertor, experiments were conducted with an unfavourable flipped divertor shape in the reversed toroidal magnetic field direction. In this new tungsten environment, a ~60% increase in electron density necessitates at least 50% more NBI power to achieve ITB formation while facing the lower tungsten divertor.

A new ITB scenario, known as FIRE (Fast Ion Regulated Enhanced) mode, has been established and extended to a higher density regime. A high $T_{i0} \sim 9$ keV has been sustained for up to 30 seconds in the USN configuration, and it has been successfully reproduced in the tungsten environment, with even longer durations, up to 48 seconds, achieved subsequently. A newly developed advanced NBI control scheme has been implemented to optimize fast ion distribution and current profile for enhanced performance while avoiding instabilities. However, higher density operation in FIRE mode remains challenging due to H-mode transitions and a decrease in the core fast-ion population, which is thought to play a role in turbulence stabilization [9]. Figure 2 (c) shows an example of a higher-density FIRE mode discharge, where ion temperature degradation is observed.

An ELM-free DTB regime has also been established. During the transition from the ELMy H-mode phase to the DTB phase, an ITB was identified exclusively in the ion thermal transport channel. The edge transport barrier was sustained in both ion and electron temperature profiles, while electron density decreased across the transition. Peeling-ballooning stability analysis suggests that ELM suppression primarily resulted from a reduced pressure gradient caused by the density decrease.

Secondly, integrated advanced scenario development is discussed, with a focus on ELM suppression as shown in Fig.2 (d) [10]. AI-driven approaches have been developed and applied to maintain high performance while suppressing ELMs using RMP [11]. Additionally, particle and heat control strategies will be addressed, particularly for impurity influx control in long-pulse operations.

Thirdly, projections of these advanced operation scenarios are explored using integrated modelling with TRIASSIC [12] for CPD. Sensitivity studies assess the range of NBI and EC heating and current drive specifications to achieve these scenarios.

Finally, future prospects are discussed, including new scenario exploration leveraging AI techniques such as reinforcement learning [13].

REFERENCES

[1] Y.-S. Na et al Nucl. Fusion 60, 086006 (2020).
[2] J.M. Park et al 29th IAEA FEC, London, UK, 2257 (2023).
[3] H.-S. Kim et al Nucl. Fusion 64, 016033 (2024).
[4] J. Chung et al Nucl. Fusion 61, 126051 (2021).
[5] H. Han, S. J. Park et al Nature 609, 269 (2022).
[6] M.W. Lee et al Nucl. Fusion 64, 086022 (2024).
[7] Y.H. Lee et al Nucl. Fusion 63, 126032 (2023).
[8] B. Kim et al Nucl. Fusion 63, 126013 (2023).
[9] Y.-S. Na et al Nature Rev. Phys., How fast ions mitigate turbulence and enhance confinement in tokamak fusion plasmas, in press.
[10] M. Kim et al Nucl. Fusion 63, 086032 (2023).
[11] S.K. Kim et al Nature Comm. 15, 3990 (2024).
[12] C.Y. Lee et al Nucl. Fusion 61, 096020 (2021).
[13] J. Seo et al Nucl. Fusion 61, 106010 (2021).

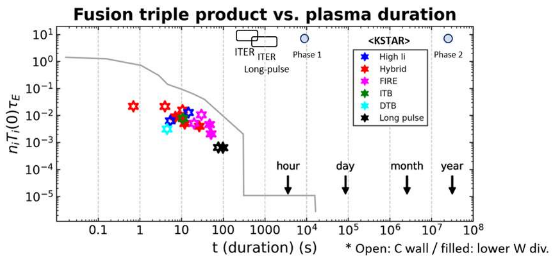

Figure 1 *Fusion triple product versus pulse duration of KSTAR advanced operation scenarios*.

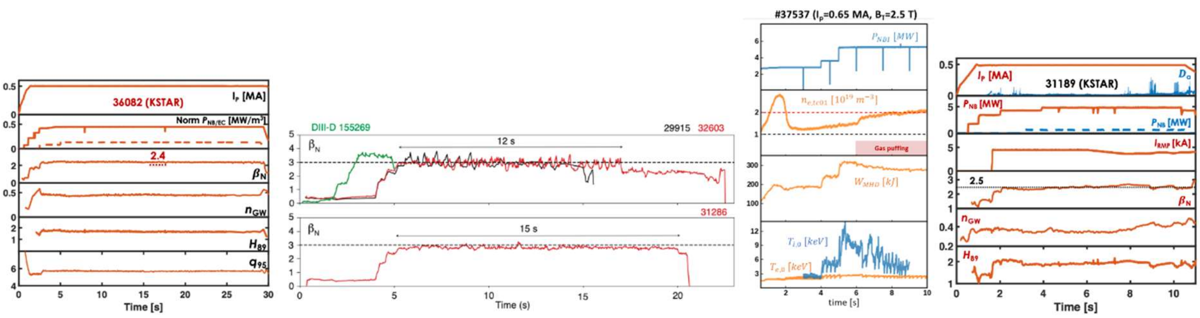

Figure 2 *(a) Long-pulse hybrid scenario with tungsten divertor, (b) high-li mode, (c) FIRE mode with a increased density, (d) Hybrid mode with RMP ELM suppression.*

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