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DEVELOPMENT OF HIGH POLOIDAL BETA SCENARIO FOR LONG-PULSE OPERATION IN COLLABORATION BETWEEN DIII-D AND KSTAR

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Abstract

The development of high poloidal beta (β_p) scenarios is crucial for steady-state tokamak operation due to their large bootstrap current fraction and favourable confinement. Building on recent progress in DIII-D, a joint DIII-D/KSTAR effort has established a new high-β_p scenario under KSTAR-like operational constraints. In DIII-D, stable operation with $H_{98} \sim 1.5$, $\beta_p \geq 3.0$, and $f_{BS} \geq 0.5$ was achieved through the formation of a large-radius internal transport barrier (ITB), even with limited heating power, slow current ramping, and delayed shaping. These results demonstrate the feasibility of high-density operation near the Greenwald limit ($f_{GW} \geq 0.9$) with full divertor detachment. Initial implementation of this scenario in KSTAR confirmed large-radius ITB formation ($\rho \sim 0.5$), providing ~30% performance improvement despite tungsten impurity accumulation and restricted neutral beam power. Although overall confinement remained limited, these findings underscore both the opportunities and challenges of applying high-β_p scenarios to superconducting long-pulse devices with tungsten divertors. Future work will focus on optimizing current profile evolution, mitigating impurity effects, and extending high-β_p operation toward reactor-relevant conditions for DEMO and pilot plants.

1. INTRODUCTION

Steady-state, long-pulse tokamak operation remains a central challenge in magnetic confinement fusion research. High-β_p operation, characterized by high bootstrap fraction and favourable confinement, is considered one of the most attractive scenarios for next-generation devices such as DEMO and fusion pilot plants (FPPs).

KSTAR has recently demonstrated a 100-second high-performance long-pulse operation with a tungsten divertor, marking a milestone in advanced tokamak research. Parallel efforts at DIII-D have shown that high-β_p plasmas with large-radius ITBs can simultaneously achieve high confinement ($H_{98y2} \geq 1.5$), density above the Greenwald limit, and improved core-edge integration. Bridging these achievements between KSTAR and DIII-D is critical for developing reactor-relevant, reproducible scenarios.

This paper provides a detailed account of these developments, highlighting the technical challenges, physics insights, and potential implications for future fusion devices. By elaborating on both the KSTAR and DIII-D perspectives, we aim to provide a comprehensive reference for the research community.

2. KSTAR HIGH-β_P SCENARIO FOR LONG-PULSE OPERATION

Since the first high-β_p discharge in 2015, KSTAR has pursued long-pulse operation based on this scenario. These efforts, combined with the recent tungsten divertor upgrade, culminated in the first successful demonstration of a high-performance plasma sustained for ~100 s (see Fig. 1b). KSTAR high-β_p discharges exhibit distinct features compared with the well-known DIII-D high-β_p regime. In particular, operation at high q_{95} ($\geq$7.0) yields high β_p ($\geq$3.0), resulting in large bootstrap current fractions favourable for long-pulse operation. Uniquely, however, central ECH plays a critical role. A representative discharge is shown in Fig. 1a. At q_{95} ~11, with 5.1 MW of NBI heating and 0.5 MW of central ECH, the plasma was stably maintained in a fully non-inductive state with β_p > 3.0.

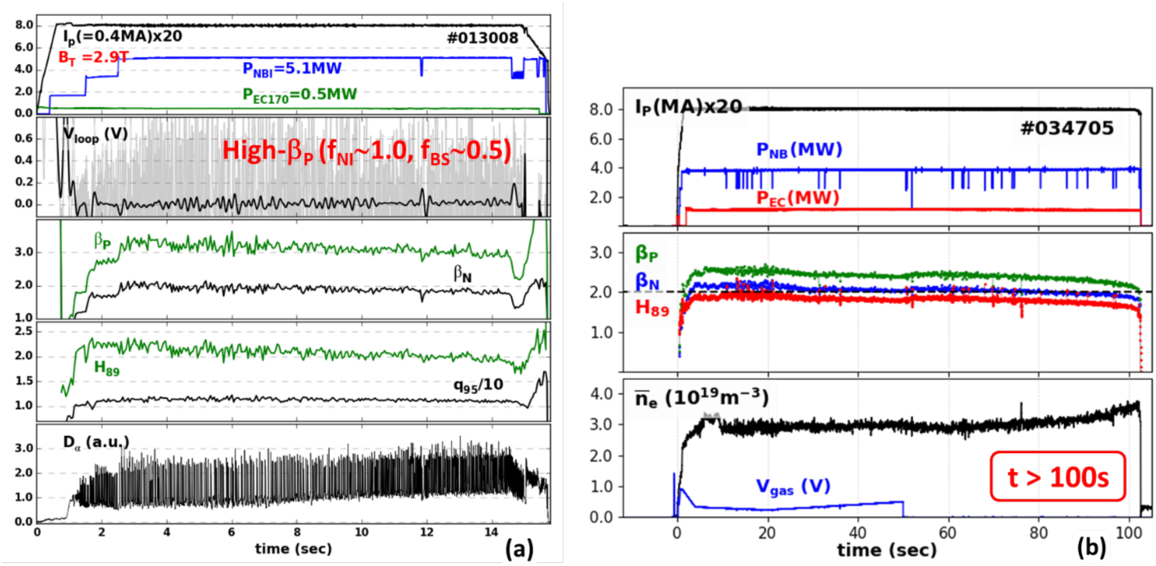

Figure 1. (a) A representative KSTAR high-β_p discharge; (b) ~100-s long-pulse high-β_p discharge.

The critical role of central ECH is highlighted in Fig. 2. Figure 2a compares discharges with and without ECH, showing performance enhancements of ~67% in total stored energy and ~75% in β_p when ECH is applied. Figure 2b demonstrates the plasma response when ECH is switched off: a substantial performance degradation occurs, though on a surprisingly long-time scale (~2.0 s), suggesting underlying physics mechanisms that require further investigation.

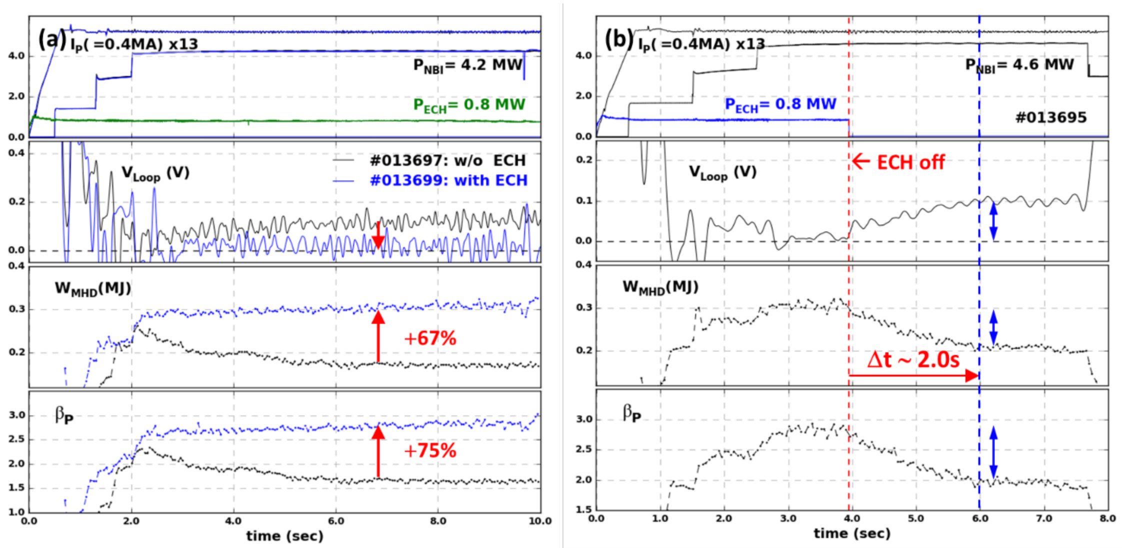

Figure 2. The important role of central ECH in high-β_p discharges

Another major difference from DIII-D is that ITBs have not been observed in KSTAR high-β_p plasmas. The observed performance improvements therefore arise from mechanisms other than ITB formation. Indirect evidence points to enhanced fast-ion confinement and beam absorption. Figure 3 (left) shows kinetic profiles of ion temperature, electron temperature, electron density, and toroidal rotation, indicating no ITB structure. However, the right-hand plots reveal a dramatic increase in absorbed NBI power and corresponding thermal energy in high-β_p discharges. TRANSP analysis suggests that, while the anomalous diffusion coefficient of fast ions in standard H-mode plasmas is ~0.4, it approaches zero in high-β_p plasmas, consistent with neoclassical transport. These results indicate that central ECH significantly improves NBI power absorption and thereby boosts plasma performance.

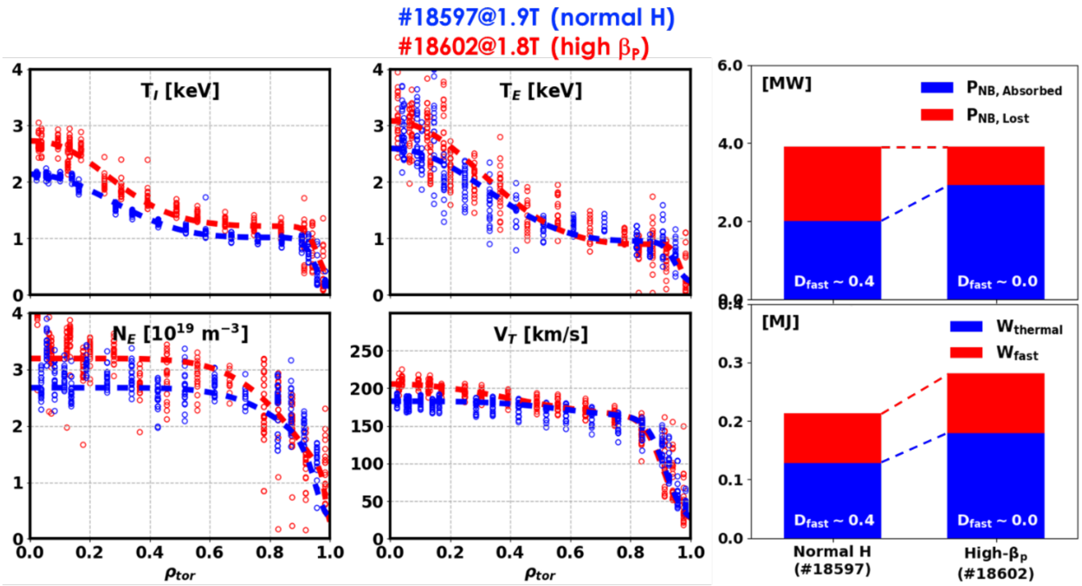

Figure 3. Kinetic profiles of high-β_p discharges and TRANSP analysis

In summary, the KSTAR high-β_p scenario exhibits distinct characteristics from conventional high-β_p operation. By achieving high β_p and sustaining large bootstrap currents, it enables long-pulse operation, culminating in the successful demonstration of ~100-s discharges. The next step for KSTAR is to advance this high-β_p scenario toward more reactor-relevant conditions. Specifically, efforts are directed toward reproducing the DIII-D high-β_p regime that couples large-radius ITB formation with higher density operation, enabling improved confinement ($H_{98y2} \geq 1.5$) under conditions applicable to future reactors.

3. KEY FEATURES OF DIII-D HIGH-β_P DISCHARGES

The most significant feature of DIII-D high-β_p discharges is the formation of large-radius internal transport barriers (ITBs), which enable superior confinement performance. Importantly, such high-performance plasmas can be sustained at densities exceeding the Greenwald limit, making this scenario highly relevant for DEMO and future fusion pilot plants (FPPs). These advantages are illustrated in Figure 4. Figure 4a shows the correlation between plasma density and thermal energy confinement using DIII-D data. For non-high-β_p discharges (shown in yellow), confinement clearly decreases with increasing density, falling sharply as f_{GW} approaches unity. In contrast, high-β_p discharges maintain strong confinement (H_{98y2} ~1.5) even at high density. Figure 4b further highlights this distinction: low-q_{95} H-mode plasmas exhibit severe degradation at high density, while high-β_p plasmas display the opposite trend, with confinement improving as density increases. These results demonstrate that achieving higher density is a key requirement for accessing the high-β_p regime and naturally facilitates divertor detachment.

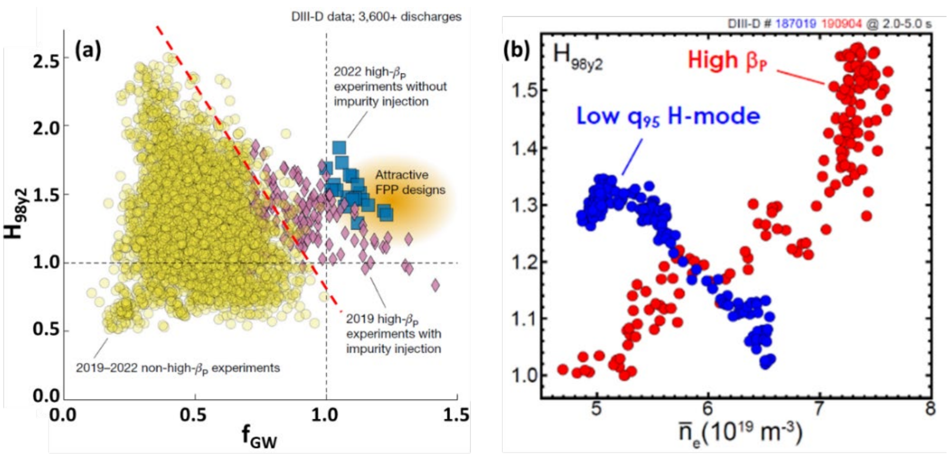

Figure 4. (a) Correlation between plasma density and H98y2; (b) contrasting trends by operational scenario

4. KEY DIFFERENCE BETWEEN KSTAR AND DIII-D HIGH-β_P SCENARIOS

Understanding the key differences between the KSTAR and DIII-D high-β_p scenarios is essential for designing experiments and addressing implementation challenges.

First, with respect to ITB formation, KSTAR relies on central electron cyclotron heating (ECH) under standard H-mode conditions. This produces a peaked current density profile early in the discharge, characterized by high li and low qmin (~1.0). In contrast, DIII-D requires a broad current profile for ITB formation, with low li and qmin > 2.0. Achieving such conditions necessitates fast Ip ramp-up, early shaping, and early L/H transition.

Second, KSTAR typically accesses the high-β_p regime at relatively low plasma density ($f_{GW} < 0.5$), whereas DIII-D favours high-density operation ($f_{GW} > 0.8$), which not only improves confinement but also supports divertor detachment.

In addition, differences in plasma shaping, aspect ratio (R/a), and available heating power must be considered. To bridge these differences, strategic experiments were first carried out in DIII-D under KSTAR-like constraints. The optimized scenario was then transferred to KSTAR for validation.

5. DEVELOPMENT OF A NEW HIGH-β_P SCENARIO BASED ON DIII-D WITH KSTAR-LIKE CONSTRAINTS

The high-β_p scenario has been developed and validated extensively in DIII-D, and successful implementation was also achieved under KSTAR-like constraints. Figure 5a shows the time evolution of a representative discharge, where a broad current profile with qmin > 2.0 was established and maintained. This configuration enabled stable high performance with $\beta_N \sim 3.0$, $\beta_p > 3.0$, and $H_{98y2} \sim 1.5$ at high plasma density ($f_{GW} \sim 0.9$). As shown in Figure 5b, strong large-radius ITBs ($\rho = 0.6$–0.7) were formed in all profiles.

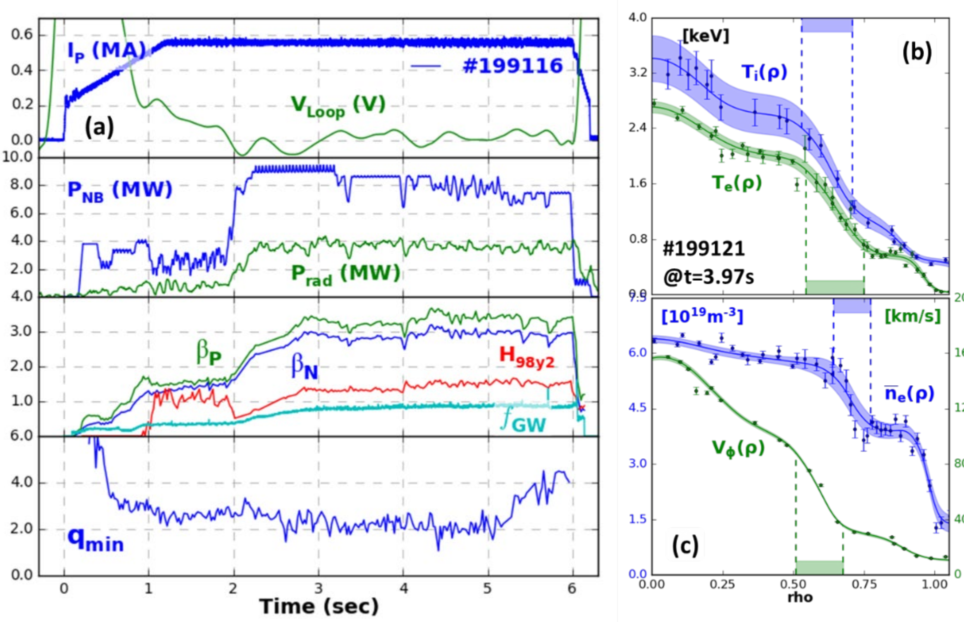

Figure 5. (a) A new high-betap discharge on DIII-D with KSTAR-like constraints. (b) Strong ITBs with large-radius are formed in all profiles.

In addition, Figure 6 demonstrates that full divertor detachment was successfully achieved through neon seeding with only a modest reduction in performance (10–20%). The right-hand plots clearly indicate detachment in divertor current, temperature, and pressure following neon injection.

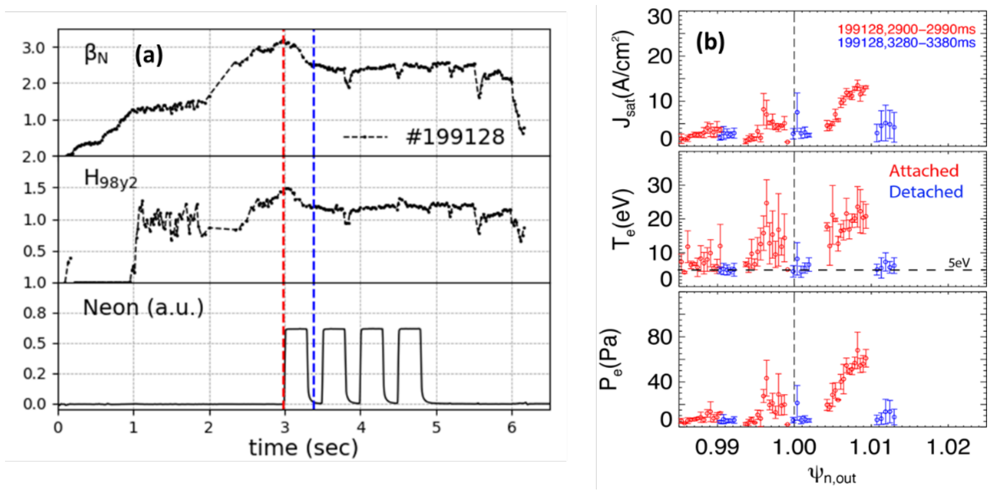

Figure 6. Full divertor detachments by neon seeding

6. IMPLEMENTATION OF THE NEW HIGH-β_P SCENARIO IN KSTAR

A new high-β_p scenario, optimized in DIII-D, was tested in KSTAR. Initial experiments, though limited, yielded encouraging results. Figure 7 shows a representative case. Up to 2 s, only pre-heating was applied to form a broad current profile (high qmin and low li), followed by main heating to increase density and β_N. Plasma density was brought near the Greenwald limit, facilitating ITB formation. qmin reached ~3.0, but li remained high (~0.9), leading to performance degradation typical of non-high-β_p discharges. Moreover, performance was sensitive to gas puffing, underscoring the need for optimized density control.

An important physics insight from DIII-D high-β_p experiments is the role of magnetic shear and the normalized pressure gradient. Access requires bypassing the unstable hill and reaching a secondary stable region. As shown in Figure 8, transiently reducing magnetic shear at low pressure gradient opens this pathway. In KSTAR, a second Ip ramp-up was introduced to alter plasma evolution, enabling marginal ITB conditions.

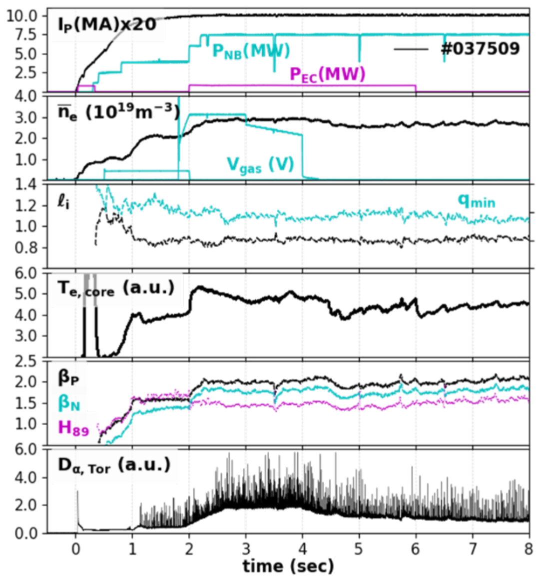

Figure 7. Initial result of the new high-β_P scenario on KSTAR

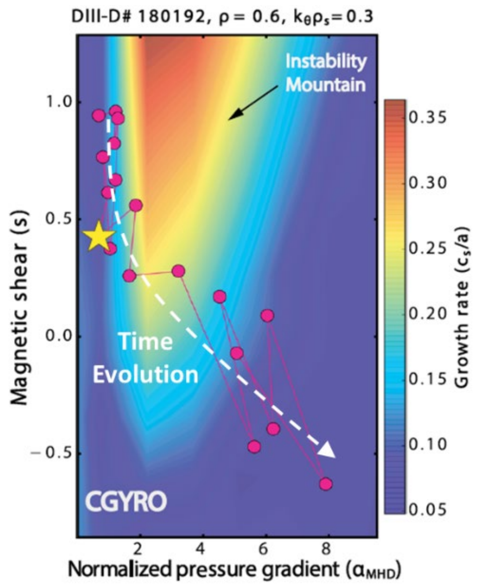

Figure 8. Importance of magnetic shear in high-β_P access

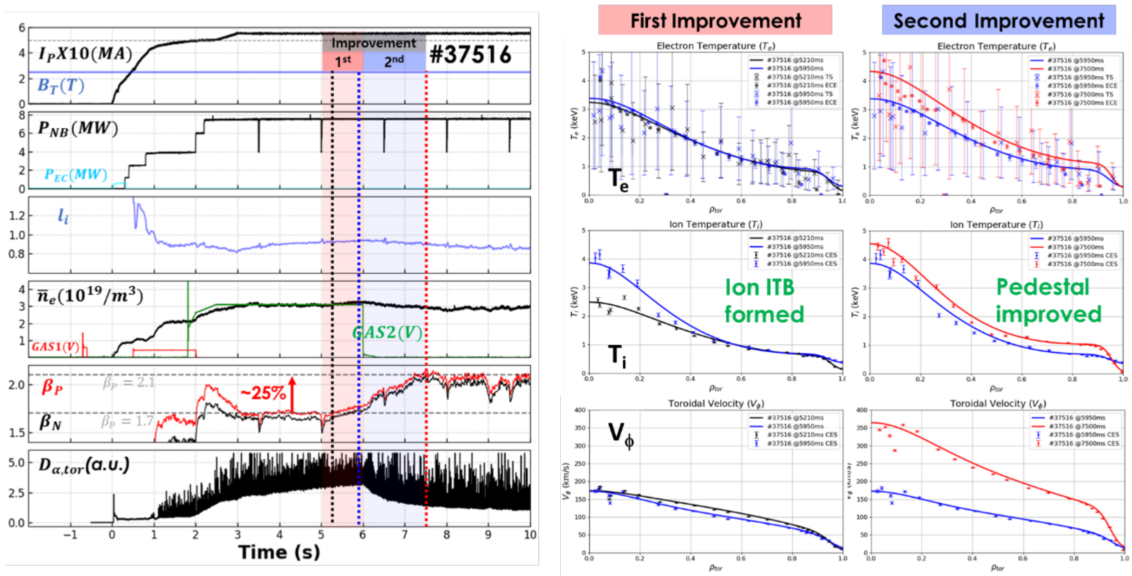

Figure 9. (a) Weak ITB formation triggered by perturbations; (b) two-step performance enhancement through ITB and pedestal improvement

Figure 9a shows that perturbations such as NBI blips can trigger ITB formation even under marginal conditions, leading to performance gains associated with ion ITB formation. Figure 9b illustrates that these gains occurred in two stages: first, ITB formation in ion temperature, followed by pedestal enhancement. Together, these produced ~25% β_N improvement at constant Ip, B_T, and heating power.

7. DISCUSSION

The results show that while DIII-D successfully developed high-β_p scenarios with large-radius ITBs under KSTAR-like constraints, implementation in KSTAR remains challenging. Key issues include establishing broad current profiles in superconducting operation, controlling tungsten accumulation, and achieving high-density operation while sustaining ITBs.

Nevertheless, weak ITB formation and pedestal improvement in KSTAR suggest a viable path forward. Further experiments should focus on optimizing magnetic shear evolution, employing real-time profile control, and testing advanced impurity mitigation.

8. SUMMARY AND CONCLUSIONS

KSTAR successfully demonstrated ~100 s long-pulse operation under tungsten environment using high-β_p scenario. DIII-D established large-radius ITB-coupled high-β_p regimes under KSTAR-like constraints, with strong confinement and density performance. Initial KSTAR experiments implementing this scenario showed encouraging, albeit challenging, results: weak ITB triggered by NBI perturbation and performance improvements via pedestal enhancement. Continued joint optimization is required to resolve access issues and extend reactor-relevant high-β_p operation toward DEMO/FPP needs.

This study underscores the necessity of international collaboration and the cross-validation of advanced tokamak scenarios. The pathway toward steady-state operation in future reactors will rely on iterative advances across multiple devices, supported by coordinated theory, modelling, and experimental campaigns.

ACKNOWLEDGEMENTS

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