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

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A collaborative effort between DIII-D and KSTAR has successfully developed a high poloidal beta scenario under KSTAR-like constraints, achieving stable high confinement ($H_{98} \sim 1.5$, $\beta_P \geq 3.0$, $f_{BS} \geq 0.5$) with a large-radius internal transport barrier. This demonstrates the feasibility of high-density, long-pulse, reactor-relevant plasma operation while also highlighting challenges such as tungsten impurity accumulation.

Recent advancements in high-performance fusion plasma operational scenarios, including the negative triangularity scenario, have been extensively investigated, each offering distinct advantages and targeted objectives. Among these, the high poloidal beta scenario has emerged as a key operational mode, particularly suited for sustained long-pulse operation due to its reliance on high bootstrap current fractions. Notably, this scenario has recently been extended into high-density regimes beyond the Greenwald density limit [1], demonstrating reactor-relevant properties and attracting significant interest. Building upon these developments, a collaborative initiative between DIII-D and KSTAR has been established to integrate expertise from advanced operational scenarios in DIII-D with KSTAR's capability for sustained long-pulse operation. This collaboration aims to develop a high-density, high-performance, long-pulse operational scenario, and the present study reports on the first findings of these efforts.

As a strategic approach, we first develop a new high poloidal beta scenario by incorporating KSTAR-specific constraints into the well-established DIII-D high poloidal beta scenario with a large-radius internal transport barrier (ITB). This scenario is designed for subsequent implementation in KSTAR's long-pulse operation, which has recently been upgraded with a tungsten divertor. The ultimate objective is to establish reactor-relevant, high-performance operational scenarios suitable for DEMO or future reactors while addressing the challenge of tungsten impurity accumulation.

To this end, preliminary experiments were conducted in DIII-D to develop a high poloidal beta scenario that incorporates key KSTAR-like constraints, including plasma shape, slow diverting, slow plasma current ramp rate, and limitations in neutral beam injection (NBI) heating. These joint efforts have yielded promising results, demonstrating that a high-performance high poloidal beta discharge can be achieved even under KSTAR-like constraints, as illustrated in Figure 1(a). Specifically, high confinement performance was stably sustained with $H_{98} \sim 1.5$, $\beta_P \geq 3.0$, and a bootstrap current fraction (f_{BS}) ≥ 0.5. As shown in Figure 1(b), the performance enhancement was primarily achieved through the formation of a large-radius ITB. In this case, a plasma of $I_P \sim 0.6$MA and $q_{95} \sim 12$ was maintained using approximately 9.0 MW of neutral beam power with density feedback control resulting in f_{GW}~0.9. Given the scale-matching considerations between DIII-D and KSTAR, these parameter ranges indicate the feasibility of achieving comparable results in KSTAR. Notably, tailoring the current density profile during the initial phase—particularly achieving a high qmin or low internal inductance (li)—was found to be essential for large-radius ITB formation. To facilitate this, the initial plasma density was deliberately maintained at a lower level, and the plasma was heated up by an early H-mode transition. The resulting broad current density profile effectively promoted the formation of a large-radius ITB, which in turn led to further enhancements in plasma confinement through well-controlled increases in beta and density.

Following these successful results in DIII-D, efforts have been undertaken to implement and validate this scenario in KSTAR, with a particular focus on addressing challenges associated with long-pulse operation. The proposed experiments were conducted as part of the KSTAR 2025 campaign. The primary anticipated challenges included the limited availability of NBI power and the adverse effects of tungsten impurity accumulation, both of which could degrade plasma performance and destabilize H-mode operation. As expected, tungsten impurity influx and accumulation significantly impacted plasma performance, presenting considerable difficulties. Nevertheless, as illustrated in Figure 1(c), a large-radius ITB (ρ~0.5) was successfully formed, leading to an approximate 33% improvement of performance. However, overall performance remained relatively constrained, with ITB formation predominantly observed in the ion temperature profile. Broadening the current density profile, particularly by achieving qmin > 2.0 as demonstrated in DIII-D, is expected to facilitate the development of a broader and more robust ITB, thereby further enhancing confinement performance.

These findings highlight both the potential and challenges associated with high poloidal beta long-pulse scenarios in KSTAR. Future work will focus on optimizing operational conditions to further enhance performance and mitigate impurity-related issues, thereby advancing towards reactor-relevant plasma operation.

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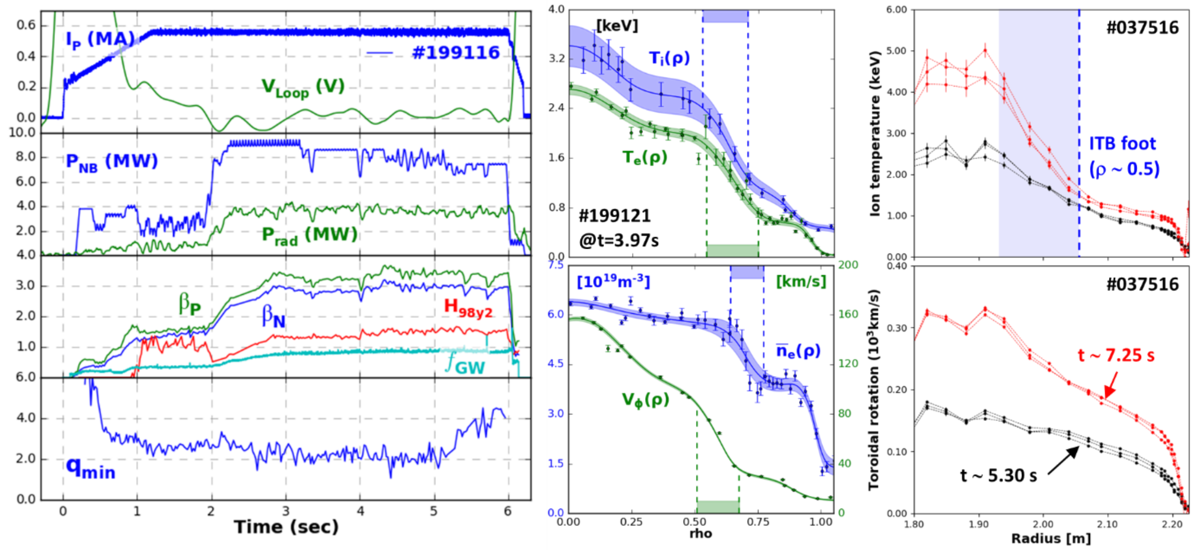

Figure 1. Obtained high poloidal beta discharges from DIII-D (left and middle) and KSTAR (right)