CONFERENCE PRE-PRINT

APPLICATIONS OF IN-SHOT CONTINUOUS NBI CONTROL SYSTEM TO THE FIRE MODE IN KSTAR

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Abstract

Advanced in-shot neutral beam control on Korean Superconducting Tokamak Advanced Research (KSTAR), with continuous and decoupled adjustment of beam power and energy, has been applied for the first time to characterize and improve Fast-Ion Regulated Enhanced (FIRE) mode. Single-discharge power scans reveal a narrow operating window with a mild magnetohydrodynamics (MHD) region, in which the sustained ion temperature is maximized as core activity weakens, indicating that simply increasing the injected beam power does not necessarily improve the core ion temperature. Reducing beam energy at constant power reshapes the beam-driven current off-axis, raises the central safety factor, removes the $q = 1$ surface, and avoids the giant sawtooth while preserving ion heating and fast-ion dilution. A two-step in-shot beam control is applied, utilizing high power for access FIRE mode and internal transport barrier formation, followed by a reduction in power to below the MHD activity threshold, which suppresses the mode and stabilizes the ion temperature at an elevated level. At equal final power, this approach exhibits a higher steady-state ion pressure than uniformly low power access, indicating the advantage of advanced neutral beam injection (NBI) control applications in enhancing the performance of FIRE mode discharge.

1. INTRODUCTION

Fast-Ion Regulated Enhancement (FIRE) mode [1, 2] is a notable high-performance scenario with an internal transport barrier (ITB) developed in the Korean Superconducting Tokamak Advanced Research (KSTAR) [3]. Its access and sustainment are nevertheless constrained by a narrow operating space that is sensitive to beam power, making reliable entry into FIRE mode challenging. The H-mode transition limits the upper boundary, and the lower boundary is limited by $n = 1$ sawtooth locking. Within this window, neutral beam injection (NBI) is the key actuator. A high fast-ion fraction from NBI suppresses ion-scale turbulence through dilution [4], enabling the formation of an ion ITB. In parallel, NBI-driven current modifies the q profile and the magnetohydrodynamics (MHD) stability of FIRE mode.

Previously, KSTAR NBI [5, 6] could not be varied during a discharge, which limited systematic exploration of how beam power and energy affect the FIRE mode characteristics. KSTAR now provides in-shot continuous control and decoupled adjustment of beam power and energy with the NBI-2 [7, 8] system. This in-shot continuous capability offers a new way to navigate the delicate landscape of FIRE mode stability within a single discharge. The separation of controls isolates the roles of ion heating and fast-ion fraction versus current drive and q-profile shaping, which permits the expansion of the FIRE mode window.

This paper reports the first integrated application of the advanced NBI control system to FIRE mode on KSTAR. Section 2 maps the FIRE operational window using in-shot power scans within a single discharge. Section 3 expands the lower boundary through energy tailoring at fixed power, avoiding sawtooth onset while preserving ion temperature. Section 4 establishes an MHD mild pathway by initiating an ITB at high power and then sustaining performance after power reduction via in-shot control.

2. FIRE MODE OPERATIONAL WINDOW AND MHD BEHAVIOR BY IN-SHOT POWER SCANS

The FIRE mode operational window is sensitive to neutral beam power, and the associated evolution of the MHD spectrum can be characterized directly using in-shot control capability. Continuous in-shot power scans were performed using the advanced NBI control while the plasma was maintained in an upper single null, low-density configuration at $B_T = 2.5\ T$.

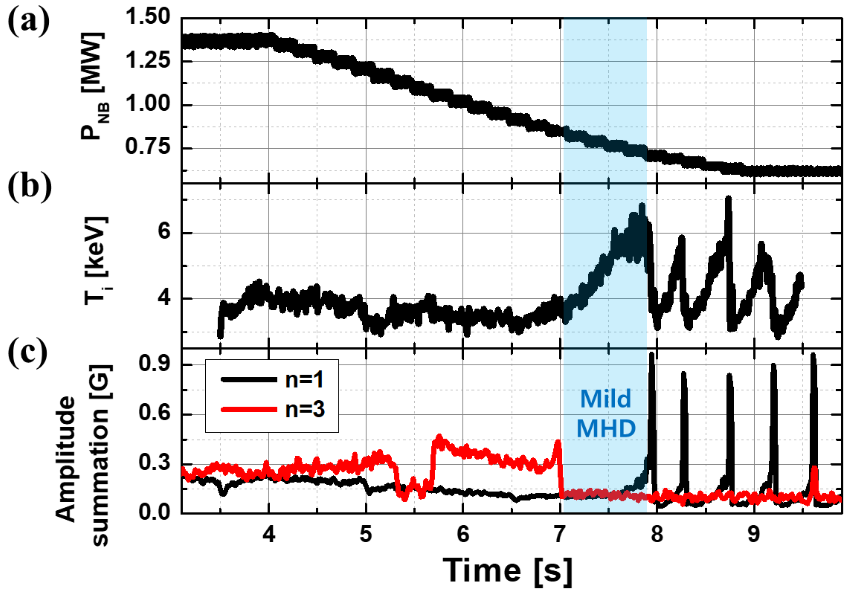

FIG. 1. (a) NBI-2A beam power, (b) core T_i, and (c) MHD activity amplitude summation of the discharge #34237. The NBI-2A beam power decreases with the use of the in-shot control capability. Despite the decreasing beam power, the ion temperature at the core increases as MHD activity is suppressed. n = 3 MHD activity is entirely suppressed at 7.0 s, and giant sawtooth appears around 7.9 s, affecting T_i performance degradation.

A representative example is discharge #34237, in which the NBI power was ramped down from a high level, as shown in Fig. 1(a). Despite the reduction in beam heating, the core T_i rose after 7.0 s as MHD activity was suppressed. This behavior indicates that, near the upper window, excessive power can drive deleterious core modes that degrade confinement. As the power was lowered into a mild MHD regime, the n = 3 activity was entirely suppressed between 7.0 s and 7.9 s. When the power was reduced further, a low-frequency giant sawtooth appeared at 7.9 s, which limited sustainment high T_i as shown in Fig. 1(b).

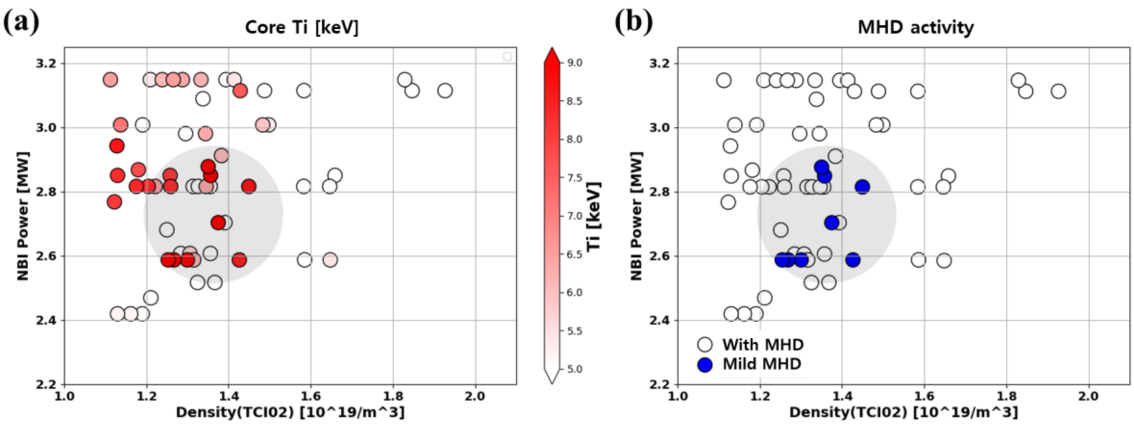

FIG. 2. (a) Ion temperature and (b) MHD activity according to plasma density and beam power in the 2.5 T FIRE mode operational window. There is a strong correlation between the mild MHD activity region and the high ion temperature region, marked by the gray circles.

A mapping using multiple in-shot scans across density and power reveals a sweet spot where MHD activity is mild and T_i reaches its highest sustained level, as shown in Figs. 2(a) and (b). Maximizing injected power does not guarantee high T_i in FIRE mode; the optimum lies below the threshold at which strong core MHD is driven. The advanced controller makes this region directly accessible by sliding to it within a single discharge and then holding or finely adjusting the power to keep MHD marginal.

3. LOWER-LIMIT EXPANSION OF FIRE MODE BY BEAM ENERGY REDUCTION AT CONSTANT BEAM POWER

The operational lower boundary of FIRE mode in KSTAR is set by the onset of giant sawtooth locking at low beam power, which terminates the discharges or significantly perturbs ion temperature. To relax this constraint without compromising ion heating, the decoupled control capability of the advanced NBI control is used to implement a constant power, variable energy strategy. This approach is demonstrated in discharge #33906, as shown in Fig. 3, where the NBI-2A beam energy was decreased from 70 keV to 55 keV at a constant power of 0.8 MW. The evolution clearly shows that sustained T_i during the beam energy ramp, and sawtooth activity is avoided in the lower beam energy condition.

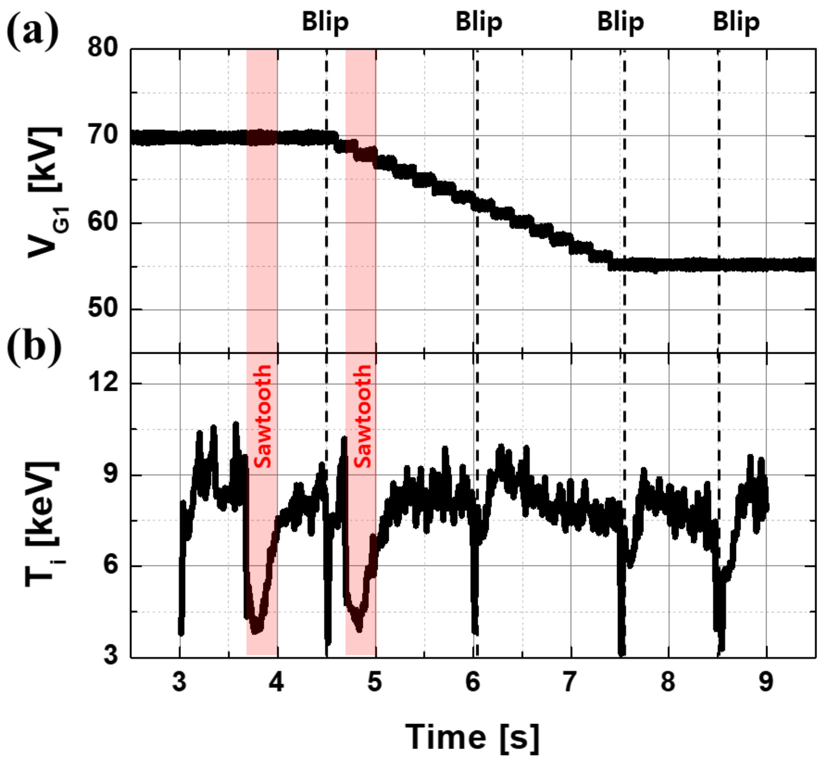

FIG. 3. (a) The NBI-2A beam energy and (b) core T_i of discharge #33906. With high beam energy, a giant sawtooth occurs, which affects T_i performance degradation. Minor plasma perturbation with NBI blips is shown in dashed lines.

The mechanism is consistent with the accompanying changes in beam-driven current from 75 keV to 55 keV; the driven current density is reduced and shifted outward, central current drive decreases, as shown in Fig. 4(a), the $q = 1$ surface is removed, and the internal kink that seeds the sawtooth is stabilized in Fig. 4(b).

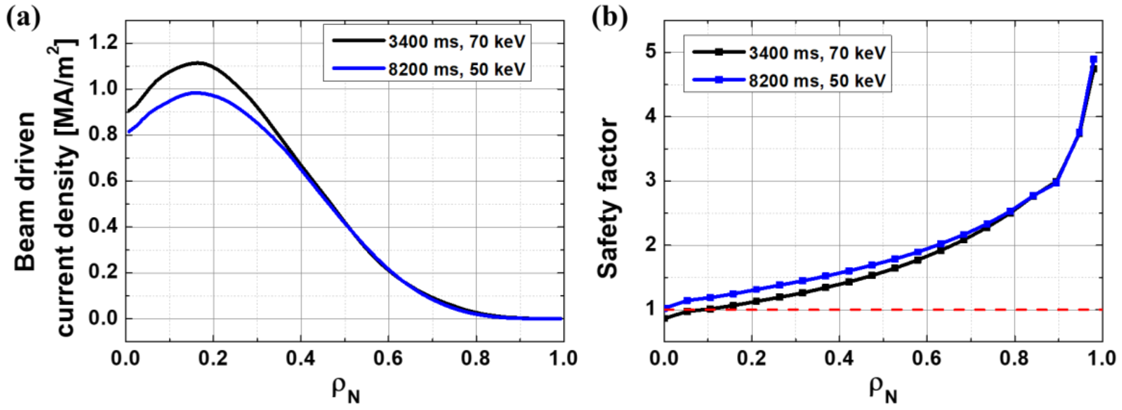

FIG. 4. (a) Changes in beam-driven current as beam energy decreases and (b) q profile at 3.4 s (black) and 8.2 s (blue). The beam-driven current shows a lower and off-axis distribution for 55 keV. The red dashed line indicates q = 1.

4. MILD MHD FIRE MODE ACCESS USING TWO-STEP IN-SHOT CONTROL

A two-step beam power and energy control was applied to enter a FIRE mode regime with only mild MHD activity while sustaining high ion temperature. The operational concept begins at sufficiently high beam power to form an ion ITB and to avoid sawtooth locking during FIRE mode access, followed by an in-shot reduction of beam power within the same discharge to weaken or entirely suppress the MHD activity that otherwise limits the steady T_i level. An application example is provided in Fig. 5, which shows the evolution of ion temperature and the dominant n = 1 mode in discharge #34249. The appearance of the n = 1 mode is associated with a substantial decrease in ion temperature performance. The n = 1 mode activity exhibits an apparent amplitude reduction as the total NBI power is lowered, in the collection of FIRE mode discharges at $B_T = 2.5\ T$ in Fig. 6. In FIRE mode discharges, complete suppression occurs below 2.65 MW. These empirical thresholds and mode characteristics inform the choice of the second-step power level.

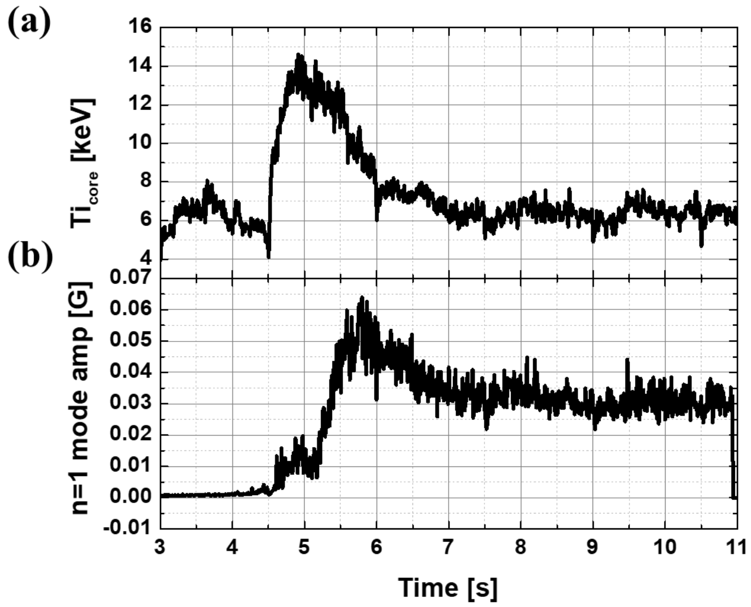

FIG. 5. (a) Core ion temperature and (b) n=1 MHD activity amplitude of discharge #34249. The occurrence of the n=1 mode and the reduction in ion temperature performance of the discharge are strongly correlated.

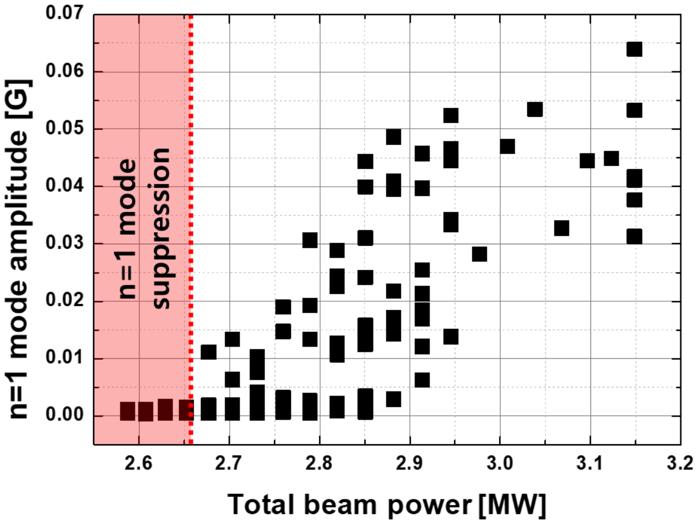

FIG. 6. n=1 MHD activity amplitude according to total injected beam power. The mode amplitude significantly decreases with reduced beam power, and it is entirely suppressed at beam power below 2.65 MW.

The beam application comparison in Fig. 7 confirms the effectiveness of the control method. A constant low-power trajectory fails to access FIRE mode and ITB formation. A continuous with high power trajectory attains a large transient T_i and then relaxes to a lower steady value as persistent $n = 1$ activity develops. In contrast, a two-step trajectory with high power for access, followed by an in-shot reduction to below the $n = 1$ threshold, maintains a substantially higher steady T_i with complete suppression of the $n = 1$ mode. At equal final power in discharges #34242 and #32423, which end at the same beam power, the access-then-reduce case achieves a higher steady ion temperature than the uniformly low power case.

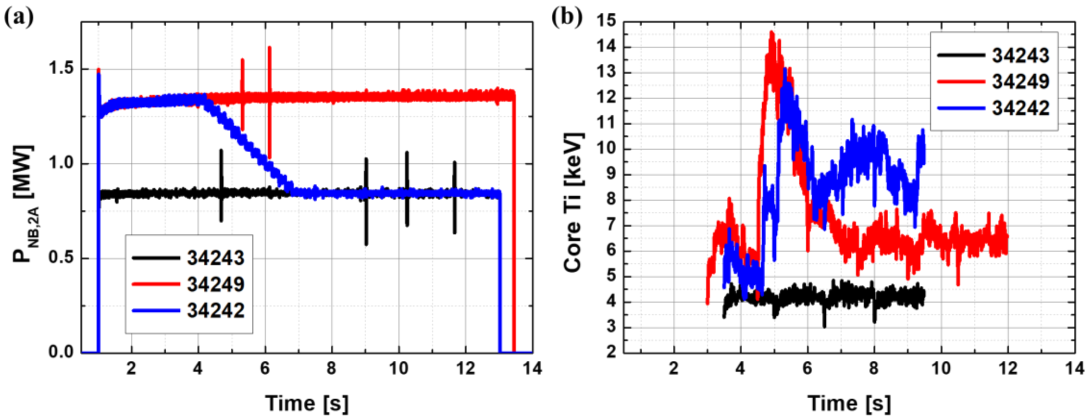

FIG. 7. (a) NBI-2A beam power and (b) ion temperature evolution of three discharges (#34243, #34249, #34242 with black, red, blue lines). Controlled beam power discharge of #34242 shows the most improved core T_i performance, even if the final level of beam power is the same as that of discharge #34243.

Fig. 8 synthesizes the FIRE mode landscape under in-shot NBI control. Constant power operation can momentarily reach the maximum ion pressure but cannot maintain it, as indicated by the black-shaded region. In contrast, in-shot power opens a red-shaded band, allowing a mild MHD state to be accessed and sustaining high, steady ion pressure. The two-step trajectory moves from high power for entry into FIRE to a reduced power level within this sustainable band, preserving the ITB while weakening the MHD drive. This control approach exposes a hidden domain of stable, high-pressure operation that fixed power beams cannot access.

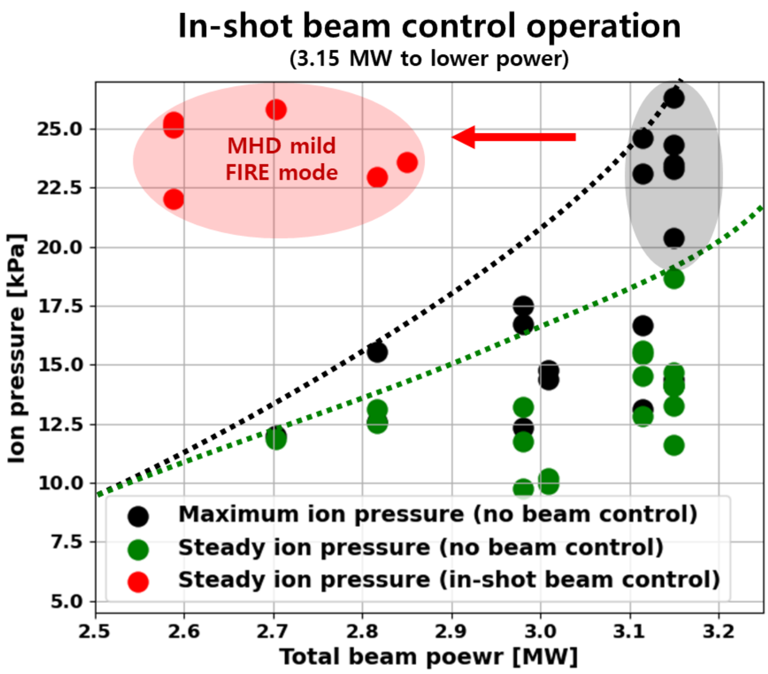

FIG. 8. MHD mild state access with in-shot beam control method. High, steady ion pressure can be accessed and sustained using NBI in-shot control. The black-shaded region indicates that the maximum ion pressure cannot be sustained with constant beam power operation. In contrast, the red-shaded region indicates the sustainable high ion pressure region using the in-shot control method.

5. SUMMARY

For the first time on KSTAR, the advanced neutral beam control system, featuring in-shot continuous adjustment and decoupled control of beam power and energy, has been applied to FIRE mode characterization and performance improvement. Single-discharge power scans map a narrow operating window and reveal a mild MHD region in which sustained T_i is maximized as core activity weakens. Excessive power is shown to drive deleterious core modes even before the H-mode boundary is reached, demonstrating that simply increasing injected power does not necessarily raise T_i in FIRE mode. Reducing beam energy at constant power reshapes the beam-driven current off-axis, raises the central safety factor, removes the q = 1 surface, and avoids giant sawtooth while preserving ion heating and fast-ion dilution.

A two-step in-shot beam control implements an access and sustain strategy for FIRE-mode operation. High power is initially applied to form an ion ITB and avoid an early giant sawtooth, followed by an in-shot reduction to just below the empirically observed n = 1 drive threshold, which suppresses the mode and stabilizes T_i at an elevated level. This beam control approach contributes to a more stable and higher-performance FIRE mode by preserving ITB quality while mitigating MHD drive, outperforming the continuous beam power approaches.

ACKNOWLEDGEMENTS

This research was supported by R&D Program of "High Performance Tokamak Plasma Research & Development (EN2501)" through the Korea Institute of Fusion Energy (KFE) funded by the Government funds, Republic of Korea.

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