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

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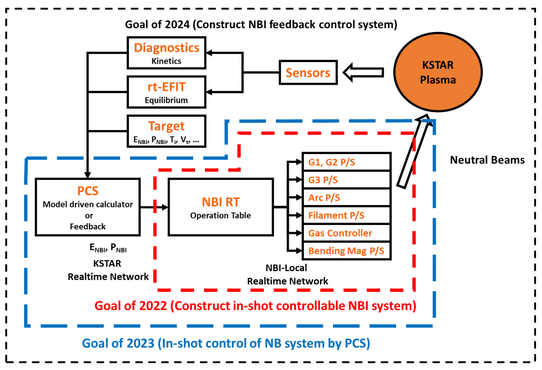
ABSTRACT

- This study introduces **advanced in-shot neutral beam injection** (NBI) control on KSTAR, applies it to the **FIRE mode** for the first time, and demonstrates enhanced plasma performance.
- **Single-shot beam power scans** reveal a narrow **mild MHD window** in which core Ti peaks; thus, more power alone does not guarantee higher Ti.
- **Lowering beam energy at fixed power** drives off-axis current and raises $q_0 > 1$, removing the q = 1 surface and avoiding giant sawtooth crashes, thereby **expanding the lower limit** while preserving core ion temperature.
- **Two-step beam control** - high power for FIRE/ITB access, followed by a drop below the MHD threshold - **suppresses MHD and stabilizes ion temperature at an elevated level**.

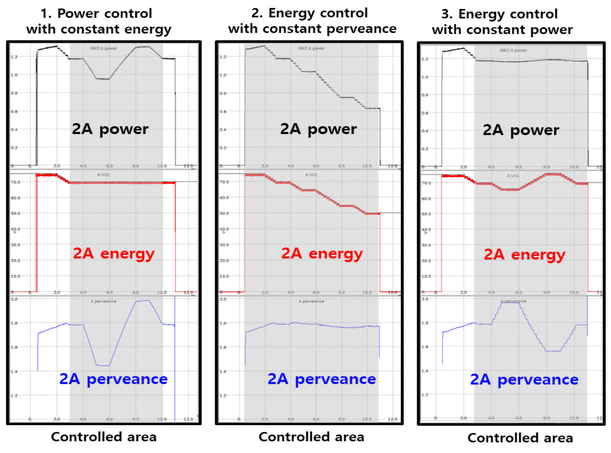
BACKGROUND - Advanced NBI control system



Overview of real-time NBI-2 control system development

In-shot continuous control

Power and energy decoupling control



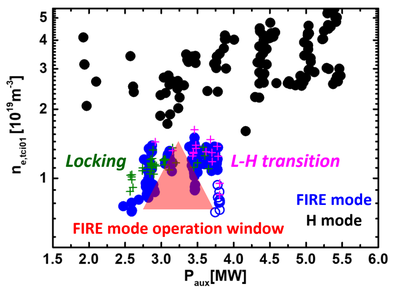
Commissioning results of advanced NBI control system

BACKGROUND - FIRE mode

Fast Ion Regulated Enhancement (FIRE) mode

[H. Han,. et al., Nature 609 269 (2022)]

- High performance (ITB)
- Long sustainment
- No severe instabilities
- However, experimental results show that the **FIRE mode window** is **very narrow** according to **NBI conditions**.

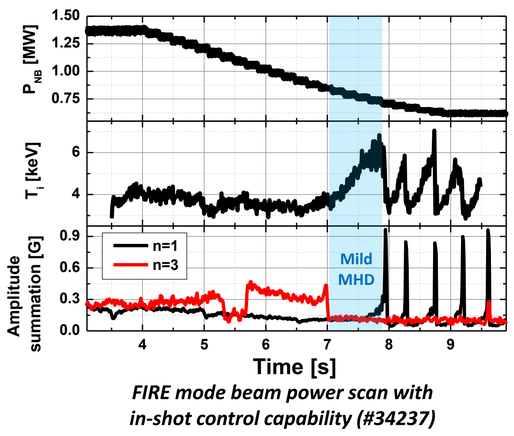


Fire mode operation window according to beam power and plasma density

Application of Advanced NBI Control to KSTAR FIRE mode

→ Understanding of **FIRE mode operation window**
→ **Lower limit expansion** using **decoupling control**
→ **MHD-free state access** using **in-shot control**

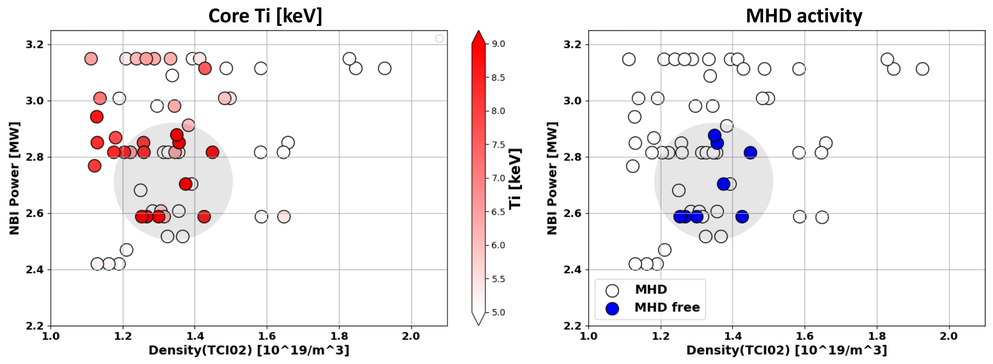
FIRE mode operational window and MHD behavior by in-shot power scans



FIRE mode beam power scan with in-shot control capability (#34237)

- **In-shot continuous control** can clearly show changes in plasma performance depending on **beam conditions** in the **narrow operation window of FIRE mode!**

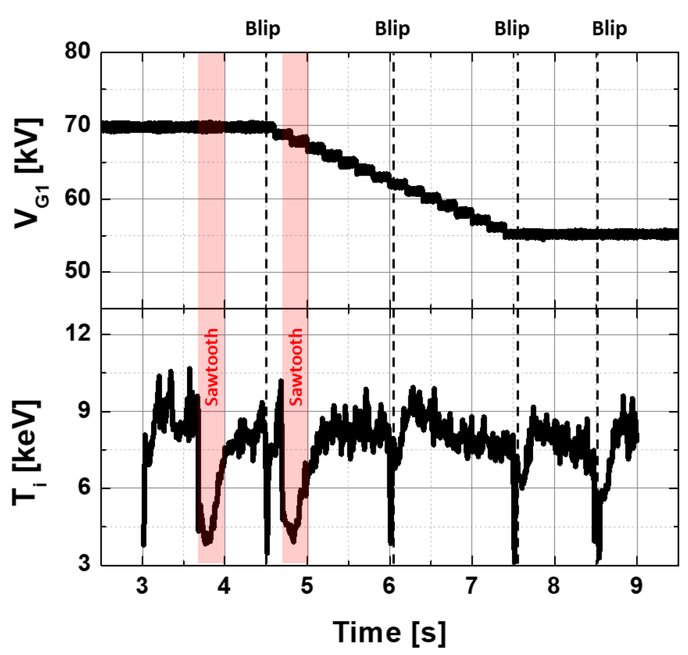
High beam power	Core MHD activity (n=2, 3)
Optimum beam power	High core T_i performance
Low beam power	Giant saw tooth



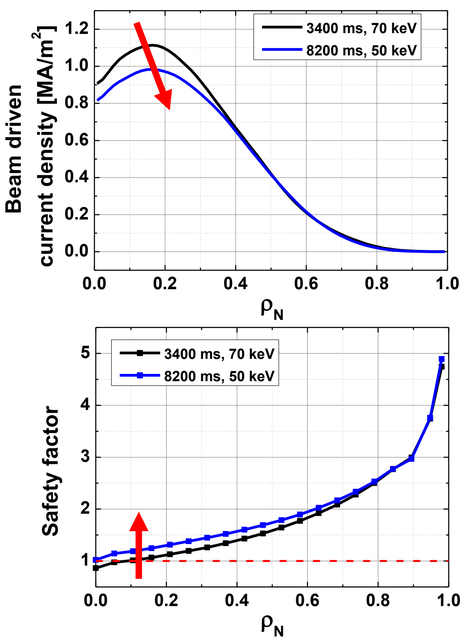
Ion temperature and MHD activity according to plasma density and beam power

- **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**.

Lower-limit expansion of FIRE mode by beam energy reduction at constant beam power



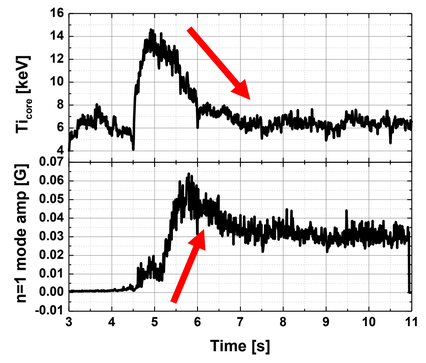
Sawtooth avoidance via beam energy reduction (#33906)



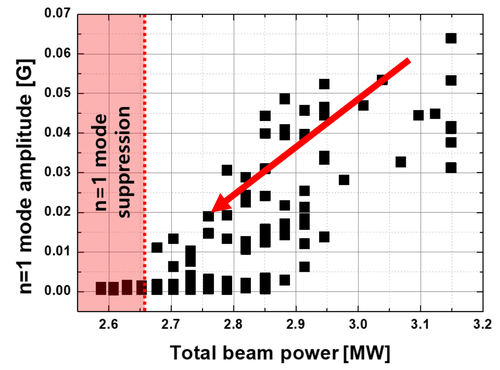
Changes in beam-driven current and q-profiles

- In a single discharge (#33906), **holding NBI power at 0.8 MW** while **lowering beam energy** from 70 → 55 keV shifted the beam-driven current off-axis, raised $q_0 > 1$ to remove the q = 1 surface, and **avoided giant sawtooth while maintaining core T_i**.
- This **fixed-power energy reduction** stabilized the core without sacrificing ion heating, effectively **extending the lower boundary** of the FIRE operating window.

Mild MHD FIRE mode access using two-step in-shot control

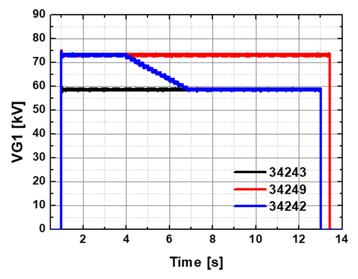


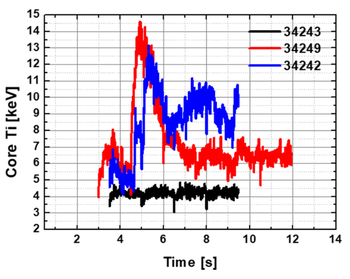
Reduction in ion temperature with the occurrence of the n = 1 mode



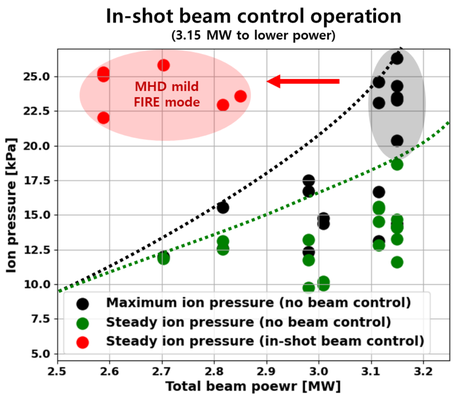
Reduction of mode amplitude with reduced beam power

- In discharge #34249, the **n = 1 mode** governs performance: its onset coincides with a **drop in core T_i**, and its amplitude **weakens as beam power is reduced**, vanishing below ~2.65 MW.





Two step beam control (#34242) vs constant beam injection (#34243, 34249)



Mild MHD FIRE mode state access with in-shot beam control

- **In-shot beam control** opens a **sustainable mild-MHD band** that enables **steady high ion pressure**, unlike constant power operation.

Summary & Future work

- On KSTAR, advanced in-shot control with decoupled power and energy mapped a narrow FIRE mode window.
- A two-step control - high-power access then sub-threshold sustain - suppressed MHD and maintained elevated T_i.
- We plan to exploit independent control of beam energy and power to optimize the fast-ion fraction and current-drive, targeting higher-density, higher-performance FIRE mode discharges.
- We will integrate real-time MHD control with advanced NBI control system to achieve high-performance long-pulse FIRE operation.

ACKNOWLEDGEMENTS

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