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First Demonstration of Stationary I-Mode Operation with Hot-Ion Core in KSTAR

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Recently, KSTAR has highlighted the successful demonstration of stationary long pulse operation of hot ion temperature plasma up to 10~15 keV without any detrimental ELM events. This was achieved by operating the plasma in a low density L-mode with an unfavourable ion grad-B configuration, instead of the conventional high density H-mode. In this report, we discuss the first successful implementation of this improved L-mode, referred to as I-mode [1], and provide an overview of its key features, particularly the highly peaked hot-ion core mode [2-3]. Also, we describe several recipes aimed at ensuring reliable access and robust sustainment of I-mode, which are linked to different physics mechanisms.

I-mode exhibits H-mode-like energy confinement with a 100~150% enhancement (up to H_{89y2}~2.5) compared to conventional L-mode, but particle confinement remains low, similar to typical L-mode. Moreover, I-mode can maintain a stationary state for over 30 seconds, which is in contrast to conventional I-mode, which is considered as a transient intermediate state between L- and H-modes. Interestingly, the toroidal rotation in this I-mode is substantially increased by ~100% or more, along with a significant increase in beam-driven neutron rate. The improvement in energy confinement is attributed to the formation of an edge transport barrier (ETB) with a similar pedestal width but reduced gradient compared to that of H-mode. However, a weakly coherent mode (WCM) observed at ~20 kHz is thought to be responsible for the lack of ETB formation in particle transport. One intriguing feature of this I-mode is its exceptionally peaked hot ion temperature, reaching up to 10~15 keV, coupled with strong toroidal rotation shear, even at low NBI heating power. This significant rise in core ion temperature seems to be associated with the strong stabilization of sawtooth instability, which is highly sensitive to plasma density. This phenomenon is similar to the so-called hot-ion mode [2-3].

To ensure reliable access and robust sustainment of this I-mode, several control techniques were investigated under diverse conditions. Achieving stable I-mode operation without mode-locking was possible through an elaborate early-neutral-beam scenario or qmin control, given the crucial role of sawtooth stabilization. Furthermore, the use of an edge-localized resonant magnetic perturbation (E-RMP) proved to be an effective means of improving the robustness of I-mode access. As a result, the I-mode operational regime was successfully expanded with respect to heating power and plasma density. Additionally, an alternative advanced scenario of an integrated operation, combining both L-to-I and I-to-H transitions in a controlled sequence, is presented, allowing for the exploration of extremely high beta operation despite limited heating power.

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References

[1] A.E. Hubbard et al, Nucl. Fusion **56**, 086003 (2016)
[2] J.F. Clarke, Nucl. Fusion **20** (1980) 563
[3] M. Knolker, et al, Plasma Phys. Control. Fusion **63** **(2021)** 025017

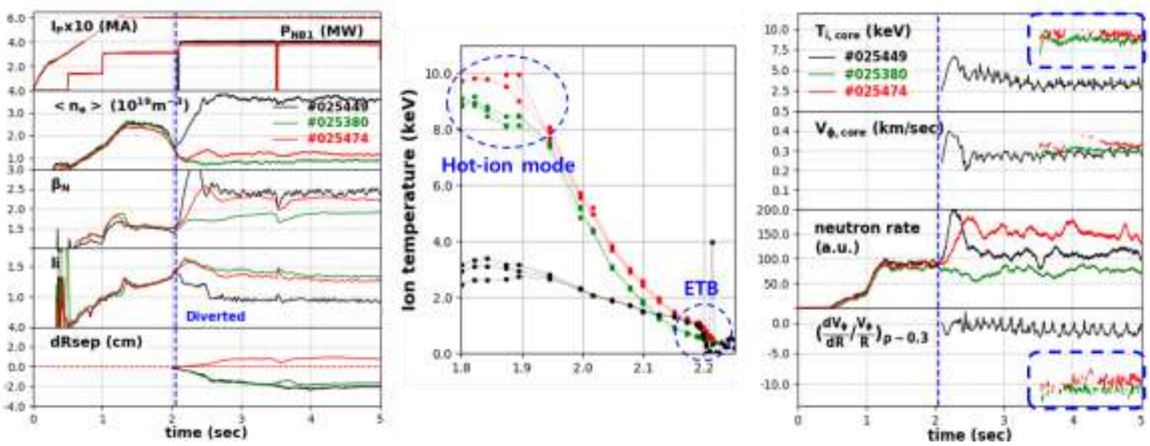

Figure 1. (Left) Comparison of H-, L-, and I-modes under similar conditions, (right) the correlation of highly peaked ion temperature profile and the rotation shear, and (middle) the observed highly peaked ion temperature profile along with I-mode driven ETB.