Recent progress and plans of inboard-limited ITB experiments on KSTAR

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It has been exploring the inboard-limited ITB (Internal Transport Barrier) as an alternative advanced operation scenario for KSTAR since 2016. The experiment of ITB formation in L-mode plasma with a marginal NBI (neutral beam injection) majority heating successfully demonstrated that the ITB is an alternative candidate to achieve a high performance regime in KSTAR. Here, the approach with the inboard limited configuration to avoid the H-mode transition prior to the formation of the ITB was effective at a given L-H transition characteristics and heating resources in KSTAR. In 2018 campaign, we have tried to extend its operation window by controlling the plasma shape and position. The key control parameters of the experiment were the triangularity (δ) and vertical position ($Z_{p)}$ of the plasma. The shape control attempted to divert the plasma to a vertically shifted Upper Single Null (USN), with a marginal touch of the inboard limiter, so that the plasma can remain in L-mode at the boundary. Here, the NBI off-axis heating provides current density profile modification and it flattens the q-profile. This was intended in the vertically shifted USN configuration. In this work, we present recent progress and plans of inboard-limited ITB experiments on KSTAR.

1. Introduction

The KSTAR uses the NBI as a majority of heating and current drive. The NBI power more than 4–5 MW under a limited L-mode was a key of the ITB access during the 2016 and 2017 campaign. The ITB formed in both ion and electron thermal channels, and performances are comparable to the usual H-mode in KSTAR [1]. Here, the approach with the inboard limited configuration to avoid the H-mode transition prior to the formation of the ITB was effective at a given L-H transition characteristics and heating resources in KSTAR. This was because that the power threshold of L-H transition became bigger than the one for the formation of ITB in the inboard-limited shape configuration. In 2016, a stable ITB discharge, which was sustained for about 7 s, was generated in a weakly reversed q-profile with the maximum available NBI power of 5.0 MW. However the maximum available NBI power was limited to 3.0 MW due to technical difficulties during the last campaign. Meanwhile the doubled capacity of the in-vessel cryopump (IVCP) allowed the plasma density control more practical.

2. Extension of ITB operation window with plasma control

In 2018 campaign, we have successfully accessed the ITB with a lower heating power about 3.0 MW. This was done by plasma shape control on triangularity (δ) and the vertical position of the plasma (Z_P) as well as we could also improve the performance with 25% lowered the 2nd gas puffing.

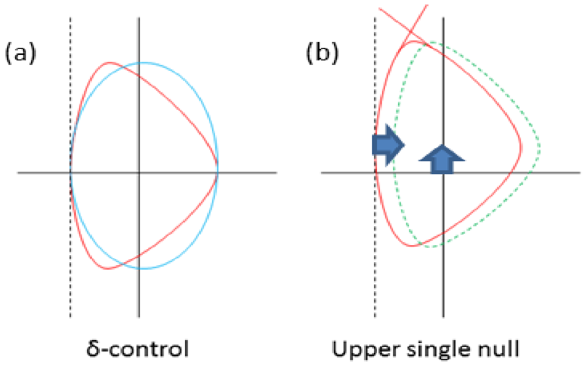

Figure 1 Concepts of the shaped ITB. (a) Inboard limited on-axis and (b) diverted off-axis heating.

We have made USN-like shape. The *dsep*, which is the distance between the closest separatrix just outside the discharge boundary and the limiter touch point, goes to 0 cm at 3.0 s. We have also slowly increased the δ about 0.3 until 5.0 s and moved up the plasma about ±5 cm from the midplane as described in the figure 1. It is known that the NBI off-axis heating provides current density profile modification and it flattens the *q*-profile. This is what we wanted to see in this configuration. Meanwhile the triangularity, δ, is a term inversely proportional to a scaled power threshold of the ITB. By changing the δ, we tried to see if there was chance to make the ITB with the lowest possible power of the NBI. This approach has been successfully demonstrated during the 2018 campaign with marginal heating power and very limited number of discharges.

Figure 2 shows the result of the shaped ITB. We have applied 2.8 MW of NBI power. The plasma control reduced the attached area to the inboard limiter and moved up the plasma slowly to feel the vertical off-axis current drive. In this particular shot, we have reduced the electron density with a less 2nd gas puffing (reduced by ~ 75%), and the formed ITB with the T_i ~ 9 keV lasted for about 1.5 s until the 8 inboard pellet injections at t = 5.0 s terminated it. This was the idea that the available NBI power was very marginal. Without the density control, the ITB lasted shorter or experienced thermal sawtooth oscillations. The stored energy and the β_N are 350 kJ and 1.6, respectively, in the discharge. The ITB foot is located roughly at R = 2.0 m which corresponds to ρ = 0.3. The ion toroidal velocity is even faster during this high T_i discharge.

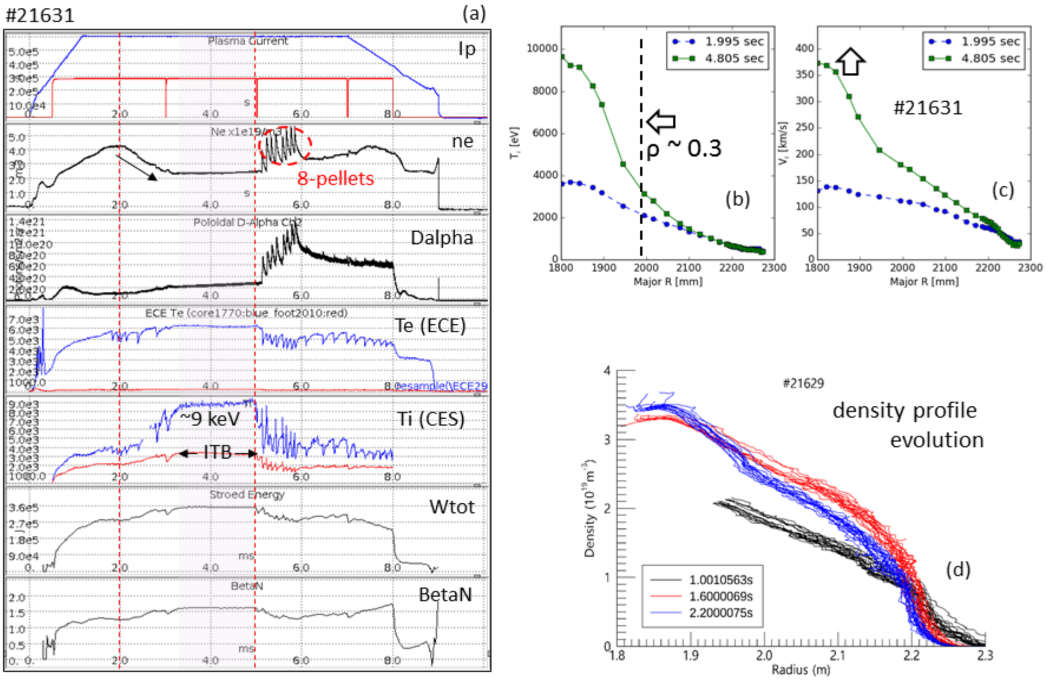

Figure 1 Time trace parameters of the shaped ITB discharge #21631 (a). The ion temperature (b) and the toroidal velocity (c) profiles show the clear formation of the internal barrier. We have also observed the evidence of particle barrier using a reflectometer system [2] for the first time during the discharge #21629 (d).

3. Initial analysis results

We have carried out initial analysis of shaped ITB discharges. No significant instability was observed in the Mirnov spectrum. Even at a particular ITB discharge with sawtooth oscillations on both ion and electron temperatures we were only able to see high *n* (= 5) dominant weak fluctuations. This MHD-resistant characteristic can be thought of as making the ITB discharge robust and reproducible, and it should be related with the shape of *q*-profile. During the first observation of the ITB in 2016, a flat *q*-profile has been observed in the central region of ρ, and the flatness tends to be monotonous to be distinguished by the difference of q_0 [3]. The q_0 is near $q = 1$ during the 2018 experiment with < 3.0 MW of NBI power, while we could observe a weakly reversed q-profile with $q_0 \sim 2$ at a higher power (~ 5.0 MW, 2016 campaign).

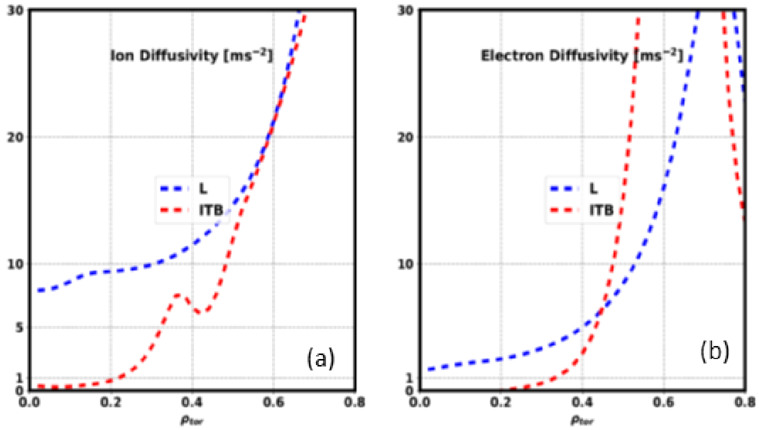

Figure 3 Initial results of TRANSP analysis show (a) the ion and (b) the electron thermal diffusivity.

Figure 3 shows an initial result of the TRANSP code analysis. We have got clear pressure profiles during the period of stable ITB, and this helped clear analysis of the discharge. Here we can see the formation of the ITB reduces both ion and electron thermal diffusion in the region of $\rho < 0.3$.

4. Summary

We have been exploring the inboard-limited ITB since 2016. The ITB scenario enhances the discharge performance in a robust way. We have also extended the ITB operation window by upshifted plasma shaping under limited NBI power up to 3.0 MW during the 2018 campaign. The shaping may reduce the ITB power threshold and enables vertically off-axis beam deposition. The q-profile showed a significant change at higher NBI power during the 2016 experiment. This will be an interesting experiment to apply this year to the shaped ITB scenario. Also it is expected that the use of additional off-axis NBI, called NBI-2, which is planned for the next campaign will enable more advanced ITB experiments.

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