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Sustainable internal transport barrier discharges in KSTAR

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The KSTAR uses the NBI (neutral beam injection) as a majority of heating and current drive and has been exploring the inboard-limited ITB (Internal Transport Barrier) as an alternative candidate to achieve a high performance regime since 2016. 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. 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. 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 [1].

However the maximum available NBI power was limited to 3 MW due to technical difficulties during the last two campaigns. Meanwhile the doubled capacity of the in-vessel cryopump (IVCP) allowed the recycling control more practical. Under these conditions, we attempted to extend the operating window by controlling the plasma shape and position, and the experiment successfully demonstrated that the ITB is accessible and sustainable with a marginal NBI heating power of about 3 MW.

The key control parameters of the experiment were the triangularity (δ) and vertical position (Z_p) of the plasma [2]. 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. To do this, 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. 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, and it was found that the duration of ITB performance was found to be related to the striking point of the upper divertor.

Figure 1 shows a result of the shaped ITB in 2018. 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. 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.

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We have carried out 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 , 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 ˜ 2 at a higher power (˜ 5.0 MW, 2016 campaign). 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 ρ < 0.3.

In 2019 campaign, the density was measured at a level of 60 - 70 % lower than in the previous year. This is a partial failure of the other diagnostic device we use, but experienced a temperature overshoot that occurred at lower density at around 3 s during the ITB onset. The high temperature gradient in the core during the overshoot caused the barrier unsustainable and this can be prevented with the appropriate additional gas puffing before the ITB onset timing. The ITB is terminated by beam blips for 10 ms for measuring the ion temperature or impurity accumulation in the vacuum vessel. At higher NBI power above 3 MW, this termination is greatly alleviated, but more technical solution was to adjust striking point of the upper divertor. KSTAR demonstrated that this plasma shape control enables ITB to be sustained for more than 10 seconds at relatively low NBI power.

REFERENCES
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