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Hybrid Scenarios in KSTAR: Experimental Approach and Physics Understanding

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Hybrid scenarios are under development in KSTAR which are defined as "stationary discharges with $\beta\_N \geq 2.4$ and $H\_89 \geq 2.0$ at $q\_95 < 6.5$ without or very mild sawtooth activities". β_N⊠3.0, H_89⊠2.4 and G-factor (≡β_N H_89/q_95^2) ⊠0.46 has been obtained simultaneously at ne/nGW~0.7 and sustained for ⊠40 τ_E during the main heating phase as shown in figure 1.

Figure 1: A representative hybrid scenario in KSTAR (Shot 18672)

The hybrid scenarios are established by several approaches; early heating, plasma current overshoot, and late heating approach. Fully non-inductive current drive has been obtained in the plasma current overshoot recipe and more stable discharges have been established with the early heating scenario by adjusting the timing of the 3rd NBI. MHD analyses show that fishbones are the main instabilities in KSTAR hybrid scenarios. Internal kink modes are appeared while ECH is applied around the on-axis region. In relatively low and high q_95 ranges, fishbones appear frequently. On the other hand, n = 2 mode, probably NTM appears dominantly in the intermediate q_95 range.

The origin of confinement enhancement is investigated in a slow transition period from the standard H-mode to the hybrid mode with 0-D power balance, 1-D kinetic profiles, linear gyro-kinetic, and pedestal stability analysis. The thermal energy confinement enhancement is thought to be mainly due to increase of the both ion and electron pedestal and some off-axis ion energy confinement improvement via stiffness weakening. The 0-D power balance analysis exhibits that the fast particle confinement is improved up to the 3rd phase of the slow transition period, whereas the thermal energy confinement only in the 3rd phase. The ion heat diffusivity is globally increased in the 3rd phase but some increase of R/L_Ti is observed in the off-axis region. Linear GKW [1] simulations show that the dominant turbulent mode is changed from TEM to ITG as the thermal confinement enhances. This results in increase of the core electron temperature. The finite β stabilisation effect plays a role together with the fast particle stabilisation effect around the core region ρ_tor=0.35. ω_(E×B) can reduce the linear growth rate of ITG in the off-axis region, ρ_tor=0.50 and 0.70 where the toroidal rotation contribution is crucial. The alpha stabilisation effect is also found at ρ_tor=0.5. ETG is estimated to sit in ρ_tor= 0.5 and 0.7 from linear gKPSP [2] simulations. The pedestal is improved due to increase of β_p and subsequent Shafranov shift. The EPED model [3] could reproduce the height of the pedestal if the feature of hybrid scenarios, a small Ohmic current fraction, and a rather flat q-profile in the core, consequently much smaller l_i than the standard EPED equilibria, is considered to calculate the Shafranov shift properly. The diamagnetic effect turns out to boost the pedestal growth.

A hypothesis to explain the confinement enhancement mechanism is suggested as shown in figure 2. The primary effect of NBI is to increase β_th, β_fast, and V_tor and alter the q- and magnetic shear profile. This increase of β can improve the pedestal stability owing to Shafranov shift which can increase the core temperatures via profile stiffness. This is the secondary effect. If the q- and magnetic shear profiles are changed to be hybrid-like, q(0)~1 with low magnetic shear, the sawtooth and the core turbulence can be mitigated or stabilised. This results in an increase of core β. If β increases larger than β_th enough to stabilise or alleviate ITG but lower than β_crit to avoid triggering an EM mode, the β stabilisation effect together with the alpha stabilisation effect could increase the core further probably via stiffness mitigation. Fast particle stabilisation can contribute as well while the fast particle confinement is improved. Increase of the toroidal rotation can increase ω_(E×B) which can contribute to stabilise ITG. All these effects come up with increase of pedestal through Shafranov shift. This is the tertiary effect, causing transition to the hybrid regime. Correlation between the NB coupling and the core and pedestal plays as a background engine to booster these effects.

Figure 2: Hypothesis of mechanism of confinement enhancement in KSTAR hybrid scenario

References
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