

# 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”.  $\beta_N \approx 3.0$ ,  $H_{89} \approx 2.4$  and G-factor ( $=\beta_N H_{89}/q_{95}^2$ )  $\approx 0.46$  has been obtained simultaneously at  $n/n_{GW} \approx 0.7$  and sustained for  $\approx 40 \tau_E$  during the main heating phase as shown in figure 1.

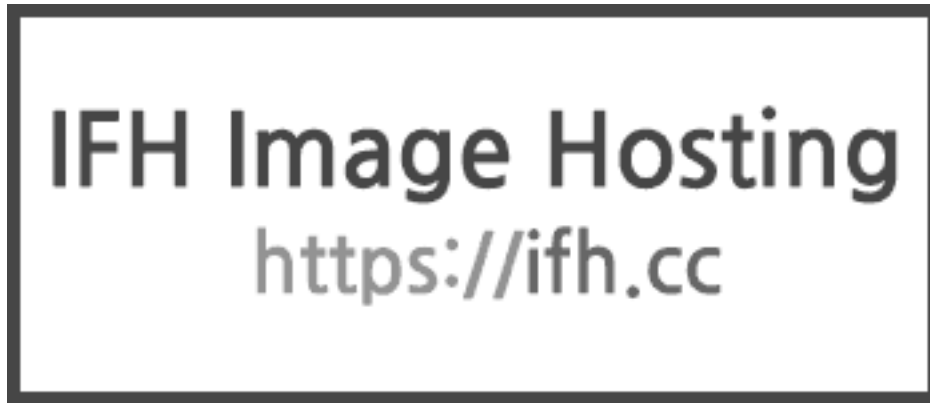


Figure 1: A representative hybrid scenario in KSTAR (Shot 18672)

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  $\beta$  stabilisation effect plays a role together with the fast particle stabilisation effect around the core region  $\rho_{tor} = 0.35$ .  $\omega_{\perp}(E \times B)$  can reduce the linear growth rate of ITG in the off-axis region,  $\rho_{tor} = 0.50$  and  $0.70$  where the toroidal rotation contribution is crucial. The alpha stabilisation effect is also found at  $\rho_{tor} = 0.5$ . ETG is estimated to sit in  $\rho_{tor} = 0.5$  and  $0.7$  from linear gKPSP [2] simulations. The pedestal is improved due to increase of  $\beta_p$  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  $\beta_{th}$ ,  $\beta_{fast}$ , and  $V_{tor}$  and alter the q- and magnetic shear profile. This increase of  $\beta$  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,  $q(0) \sim 1$  with low magnetic shear, the sawtooth and the core turbulence can be mitigated or stabilised. This results in an increase of core  $\beta$ . If  $\beta$  increases larger than  $\beta_{th}$  enough to stabilise or alleviate ITG but lower than  $\beta_{crit}$  to avoid triggering an EM mode, the  $\beta$  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  $\omega_{(E \times B)}$  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.

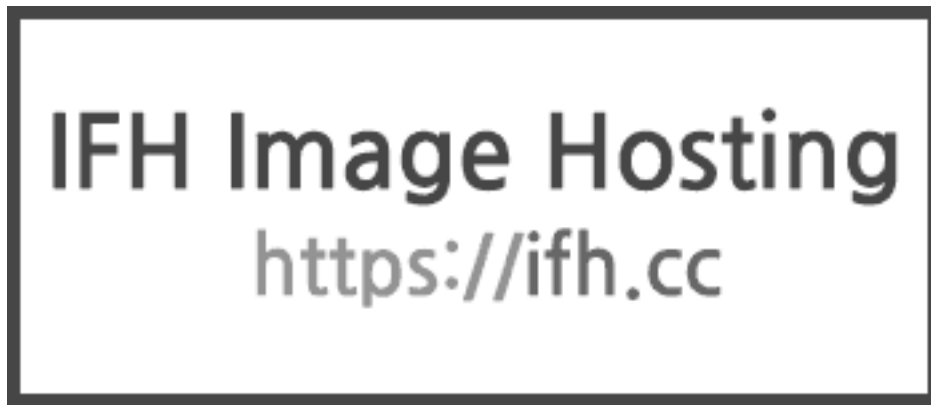


Figure 2: Hypothesis of mechanism of confinement enhancement in KSTAR hybrid scenario

#### References

- [1 ] Peeters A. G. et al 2009 Comput. Phys. Commun. 180-12 2650–2672
- [2 ] Kwon J.-M. et al 2017 Comp. Phys. Communications 215 81
- [3 ] Snyder P.B. et al 2009 Phys. Plasmas 16 056118

#### Affiliation

Seoul National University

#### Country or International Organization

Korea, Republic of

**Primary author:** NA, Yong-Su (Seoul National University)

**Co-authors:** LEE, Young Ho (Seoul National University, Korea); Mr BYUN, Cheolsik (Seoul National University); KIM, SangKyeun (Seoul National University); LEE, Chanyoung (Seoul National University); Ms PARK, Minseo (SNU, South Korea); YANG, SeongMoo (Princeton Plasma Physics Laboratory); Mr KIM, Boseong (Seoul National University); JEON, YoungMu (National Fusion Research Institute); CHOI, Gyungjin (University of California, Irvine); CITRIN, Jonathan (FOM DIFFER - Dutch Institute for Fundamental Energy Research); JUHN, June-Woo (Seoul National University); KANG, Jisung (National Fusion Research Institute); KIM, HYUNSEOK (National Fusion Research Institute); KIM, Jayhyun (National Fusion Research Institute); KO, Won Ha (KRFRI); KWON, Jae-Min (National Fusion Research Institute); LEE, Woochang (National Fusion Research Institute); Dr WOO, Minho (National Fusion Research Institute); YI, Sumin (National Fusion Research Institute); YOON, Si-Woo (National Fusion Research Institute); YUN, Gunsu (Pohang University of Science and Technology)

**Presenter:** NA, Yong-Su (Seoul National University)

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