Hybrid scenarios in KSTAR: Experimental Approach and Physics Understanding

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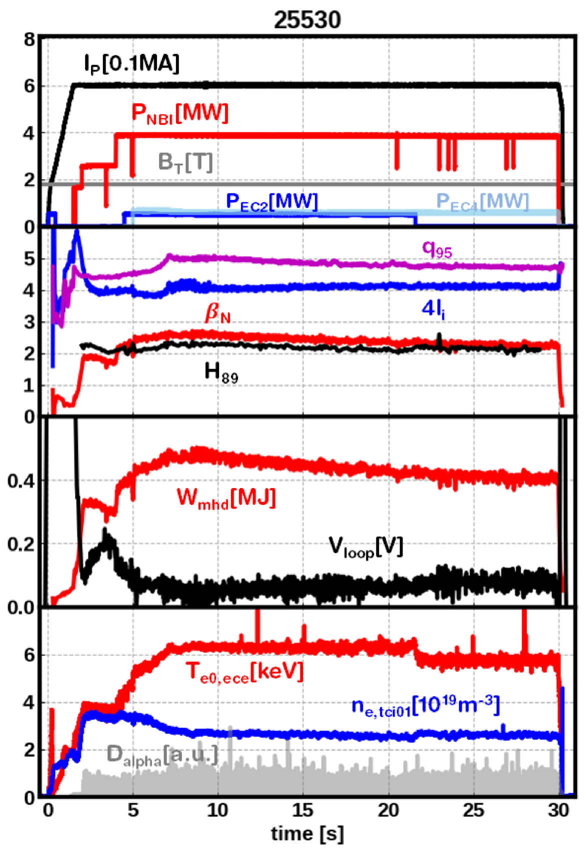
Introduction

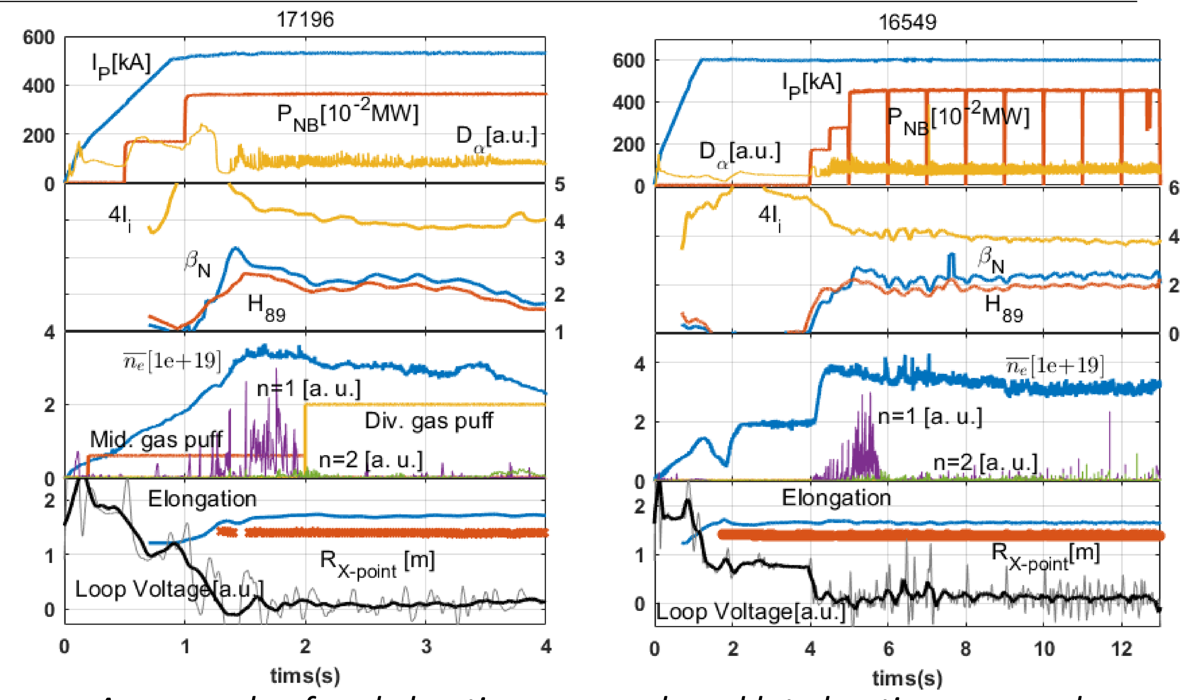
Definition of KSTAR Hybrid scenario

- Stationary discharges with $\beta_N \geq 2.4$ and $H_{89} \geq 2.0$ at $q_{95} < 6.5$ without or very mild sawtooth (ST) activities
- A representative long pulse hybrid scenario for the 2020 KSTAR campaign which sustained $\beta_N \lesssim 2.5$, $H_{89} \lesssim 2.3$ during the main heating phase



A representative long pulse hybrid scenario in KSTAR (pulse 25530)

Experimental approach to establish hybrid scenario



An example of early heating approach and late heating approach

Early heating approach

- Being widely used to obtain hybrid scenario in various tokamak devices [1-4]
- Delaying the current diffusion so as to avoid ST activity

Late heating approach

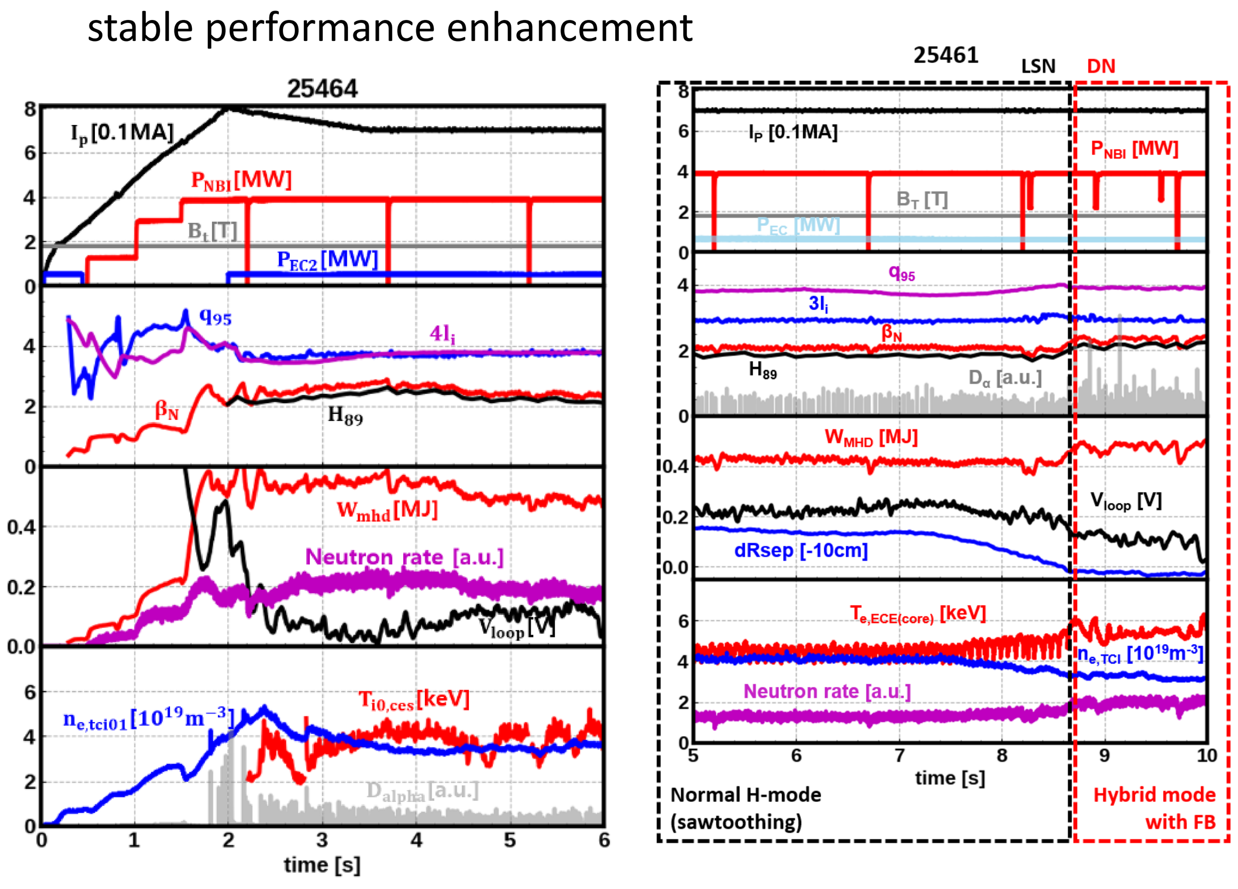
- Applying the full heating in the current flattop phase to obtain stable performance enhancement

Current overshoot approach

- Based on ITG theory [5], core confinement enhanced by favorable magnetic shear configuration → Vanished after current diffusion
- ELM frequency increases → line average density decreases → fast particle content increases → MHD mode transition (ST → FB)

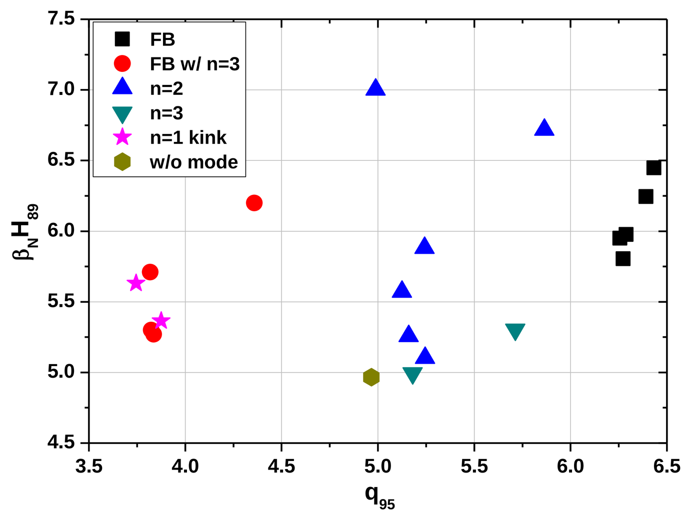
Double null configuration approach

- Peeling component stabilized by 'active' X-point [6] → more frequent ELMs by the edge PBM stability theory [7]
- Core temperature increase via core stiffness due to reduced density
- MHD mode transition (ST → FB) with reduced electron density and increased fast ion confinement



An example of current overshoot approach and double-null configuration

MHD activities in hybrid scenarios

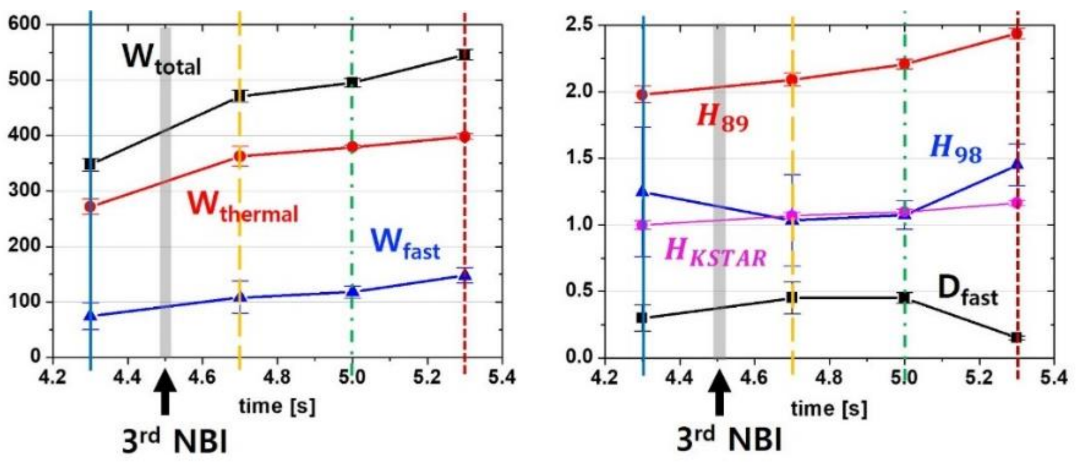


Dominant modes

Low q_{95}	Intermediate q_{95}	High q_{95}
FB w/ n=3 mode or n=1 kink	n=2 mode (NTM)	FB w/o other modes

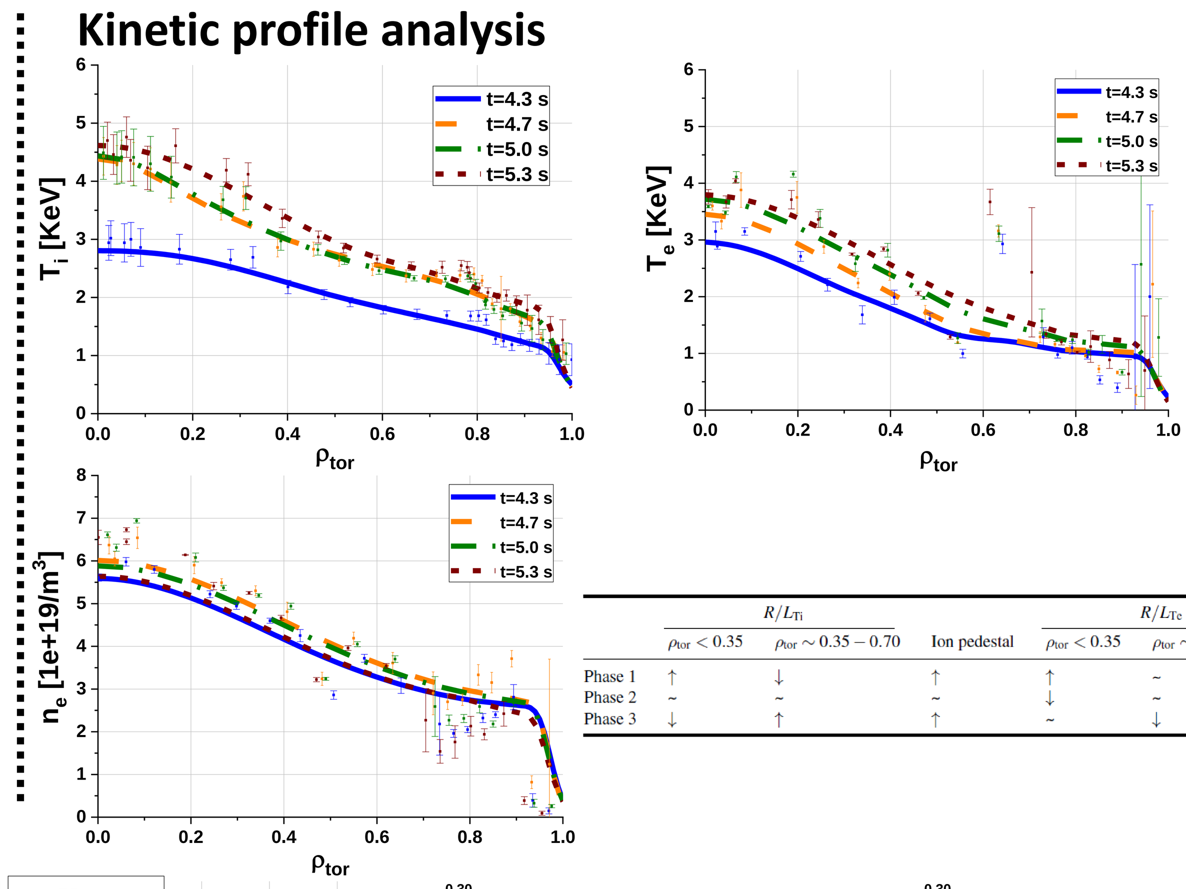
Origin of confinement enhancement in a slow transition phase [11]

Performance analysis



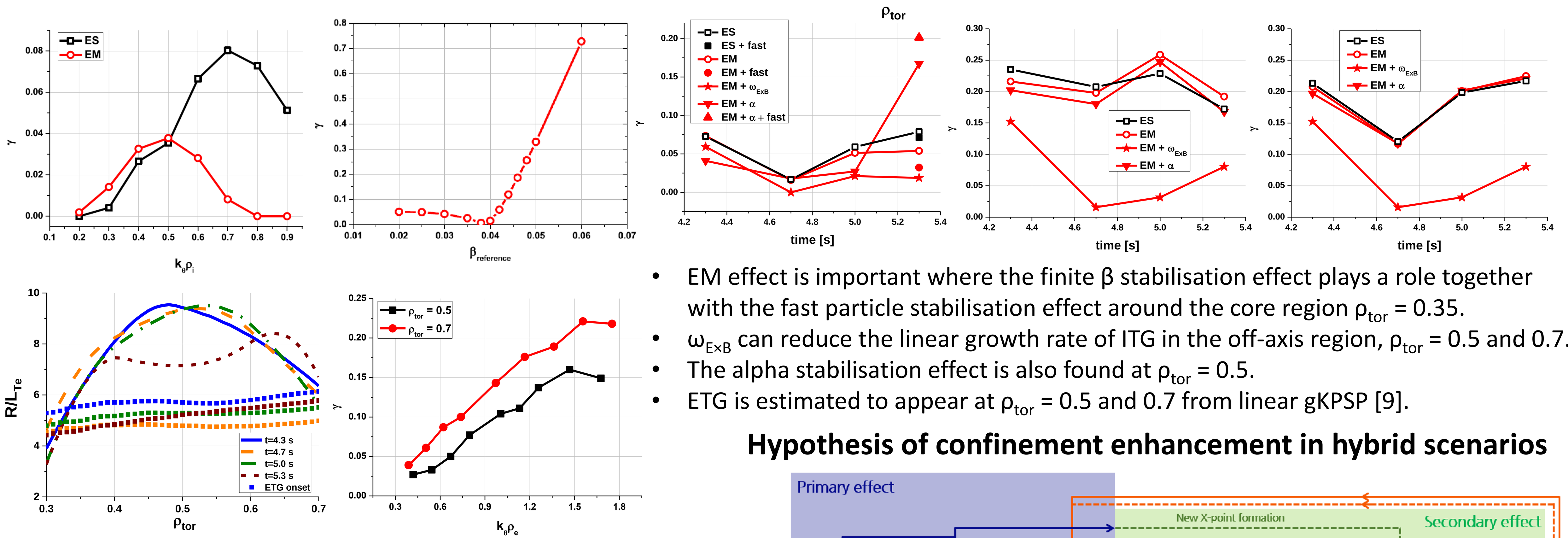
- Increase of H_{89} without H_{98} increase (4.3-5.0 s)
- Thermal confinement enhancement (5.0-5.3 s)

Kinetic profile analysis



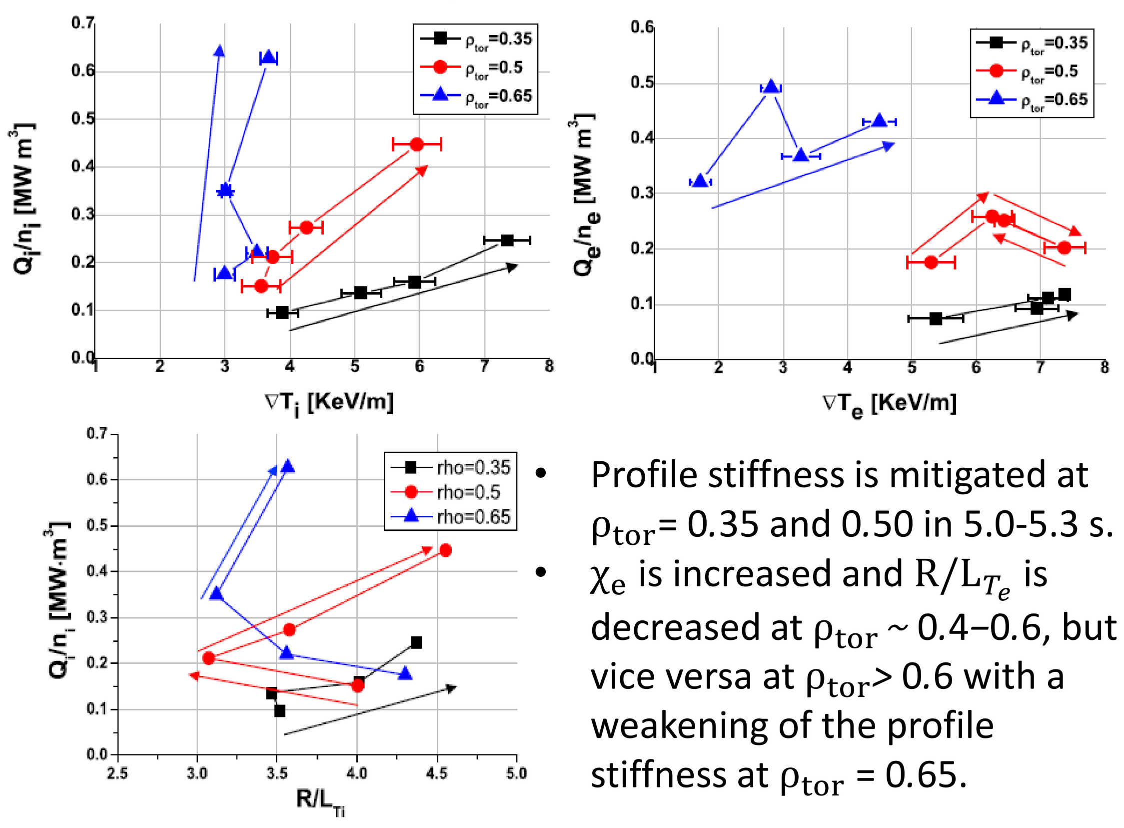
	R/L_{Ti}			R/L_{Te}		
	$\rho_{tor} < 0.35$	$\rho_{tor} \sim 0.35-0.70$	Ion pedestal	$\rho_{tor} < 0.35$	$\rho_{tor} \sim 0.35-0.70$	Electron pedestal
Phase 1	↑	↓	↑	↑	~	~
Phase 2	~	~	~	↓	~	↑
Phase 3	↓	↑	↑	~	↓	↑

Linear gyro-kinetic analysis



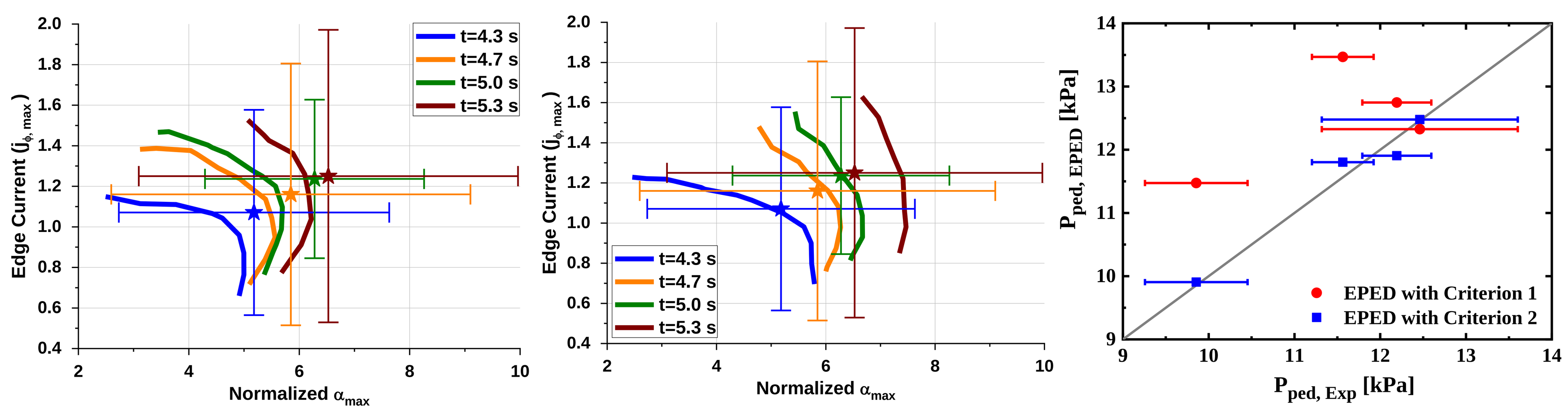
- EM effect is important where the finite β stabilisation effect plays a role together with the fast particle stabilisation effect around the core region $\rho_{tor} = 0.35$.
- $\omega_{E\times B}$ can reduce the linear growth rate of ITG in the off-axis region, $\rho_{tor} = 0.5$ and 0.7.
- The alpha stabilisation effect is also found at $\rho_{tor} = 0.5$.
- ETG is estimated to appear at $\rho_{tor} = 0.5$ and 0.7 from linear gKPSP [9].

Power balance analysis



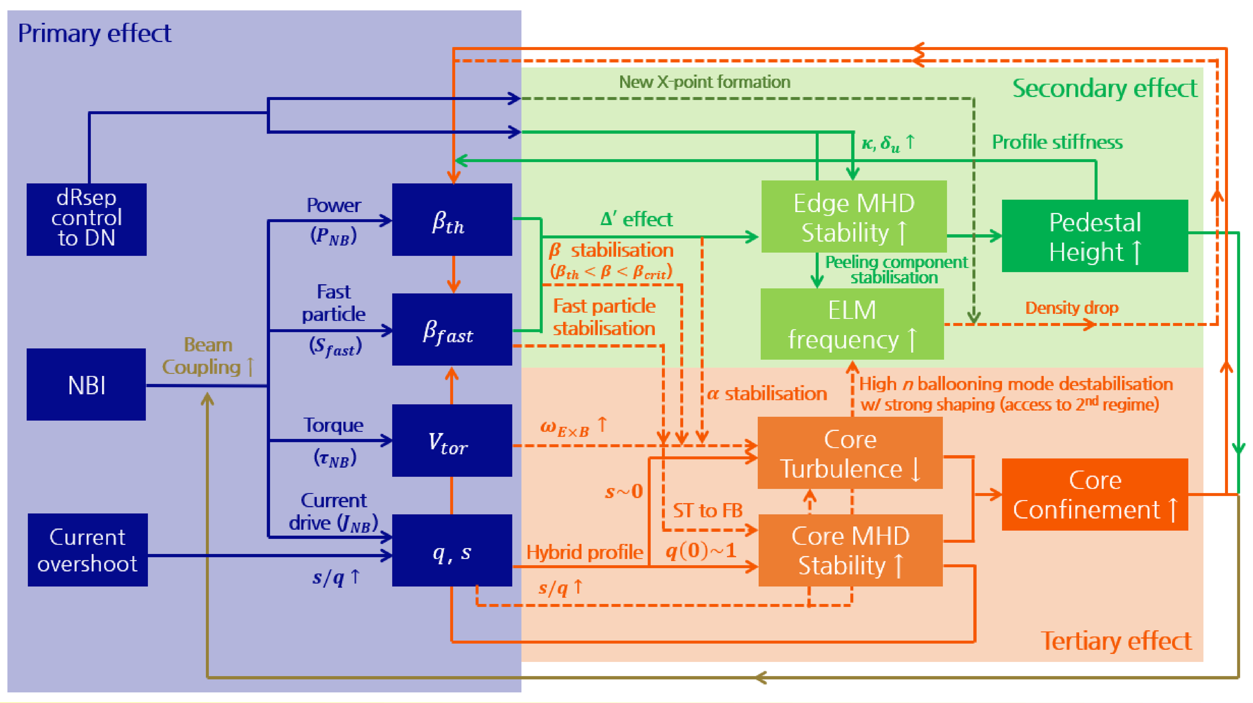
- Profile stiffness is mitigated at $\rho_{tor} = 0.35$ and 0.50 in 5.0-5.3 s.
- χ_e is increased and R/L_{T_e} is decreased at $\rho_{tor} \sim 0.4-0.6$, but vice versa at $\rho_{tor} > 0.6$ with a weakening of the profile stiffness at $\rho_{tor} = 0.65$.

Pedestal stability analysis



- The stability boundary is expanded and the diamagnetic effect boosts the pedestal growth.
- The pedestal is improved due to increase of β_p and subsequent Shafranov shift.
- The EPED model [10] could reproduce the height of the pedestal if experimental li is used.

Hypothesis of confinement enhancement in hybrid scenarios



Conclusion

- The hybrid scenario is defined as a stationary discharge of with $\beta_N \geqslant 2.4$ and $H_{89} \geqslant 2.0$ at $q_{95} < 6.5$ without or with very mild sawtooth activities in KSTAR.
- Long pulse operation has been established up to ~30 s but showing some performance degradation.
- Hybrid scenarios have been established by early heating, late heating, plasma current overshoot, and DN configuration approach.
- The reasons for confinement enhancement are studied for a representative discharge of KSTAR hybrid scenarios in this transition period. a comprehensive confinement enhancement mechanism has been proposed by considering the core-edge interplay.

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