Long-pulse ELM-free H-mode regime with feedback-controlled detachment under boronized metal wall in EAST

by

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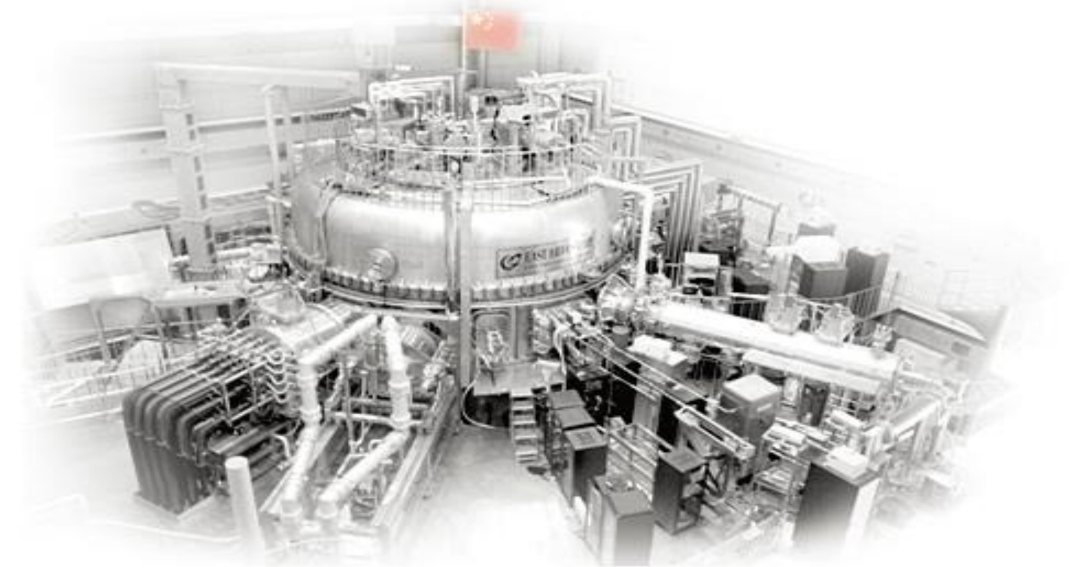

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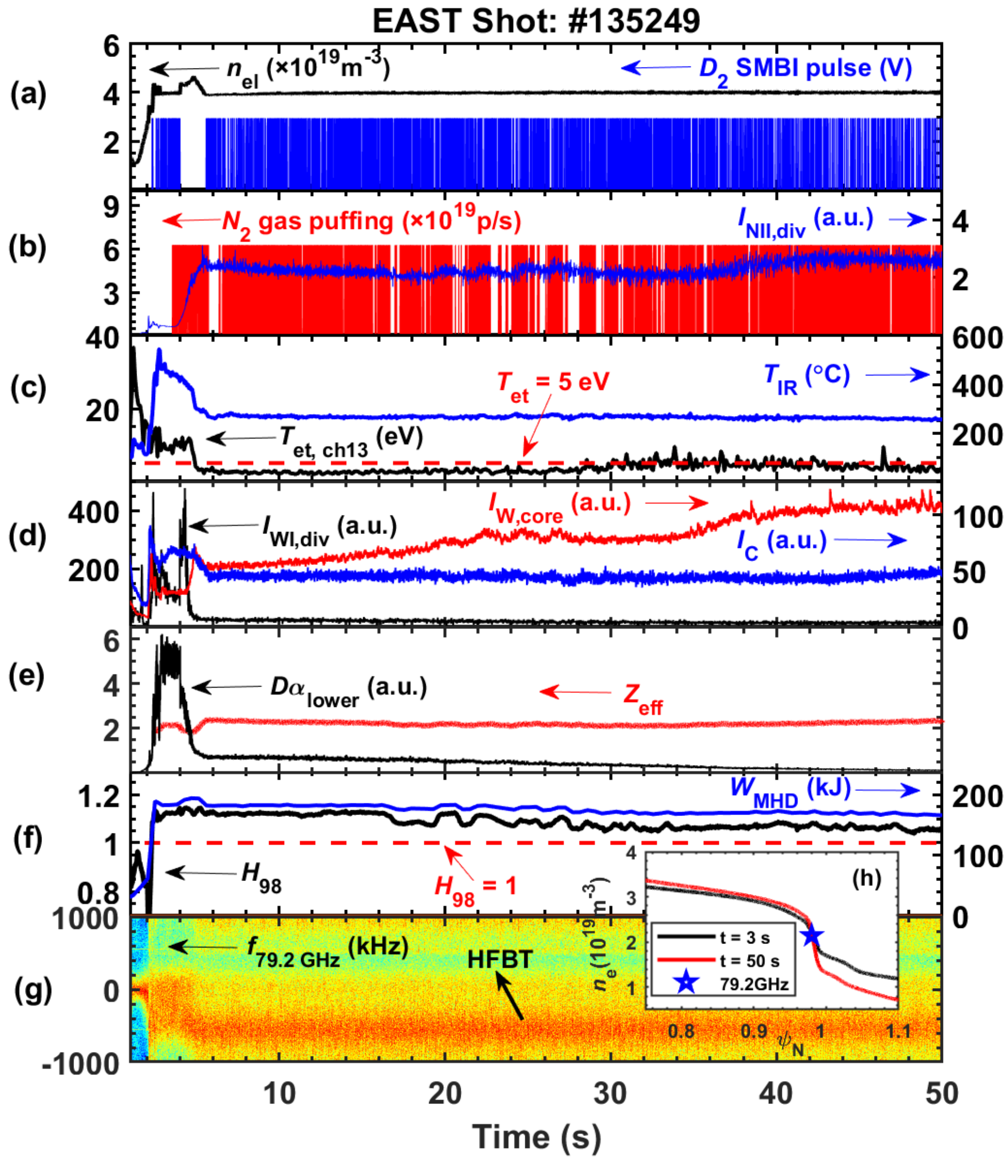
Takeaway: >50s long-pulse ELM-free H-mode regime with feedback-controlled divertor detachment under boronized metal wall in EAST

- P_{EC}~2.5MW + P_{LHCD}~1.9MW = 2.2 $P_{L\text{-}H}$
- β_N ~1.36, β_P~1.55, l_i~1.2, q_0~1, κ~1.6, δ_l~0.66, no ITB
- Lower signal null divertor configuration with dR_{sep}~-2 cm
- Plasma-limiter-surface outer gap dR_{out}~5.9 cm
- n_{el}~61%n_{GW}, T_{e0}~4.7 keV, T_{i0}~1.1 keV, $f_{rad}=P_{rad}/P_{inj}$ = 29%

- **Divertor detachment leads to an enhanced pumping and reduced ionization of recycling neutrals in the divertor and a significant increase of pedestal electron temperature gradient, which in turn excites a High-Frequency Broadband Turbulence (HFBT) in the pedestal gradient region.**
- **Gyrokinetic simulations with GENE and CGYRO codes suggest the HFBT being η_e-TEM, driving outward particle and electron heat transport, which can be excited in the low-collisionality pedestal of ITER and future fusion reactors.**
- **The expected lower density gradient, ExB shear and collisionality in the ITER pedestal will even facilitate the excitation of η_e-TEM, making this pedestal regime a potential candidate in ITER.**



Outline

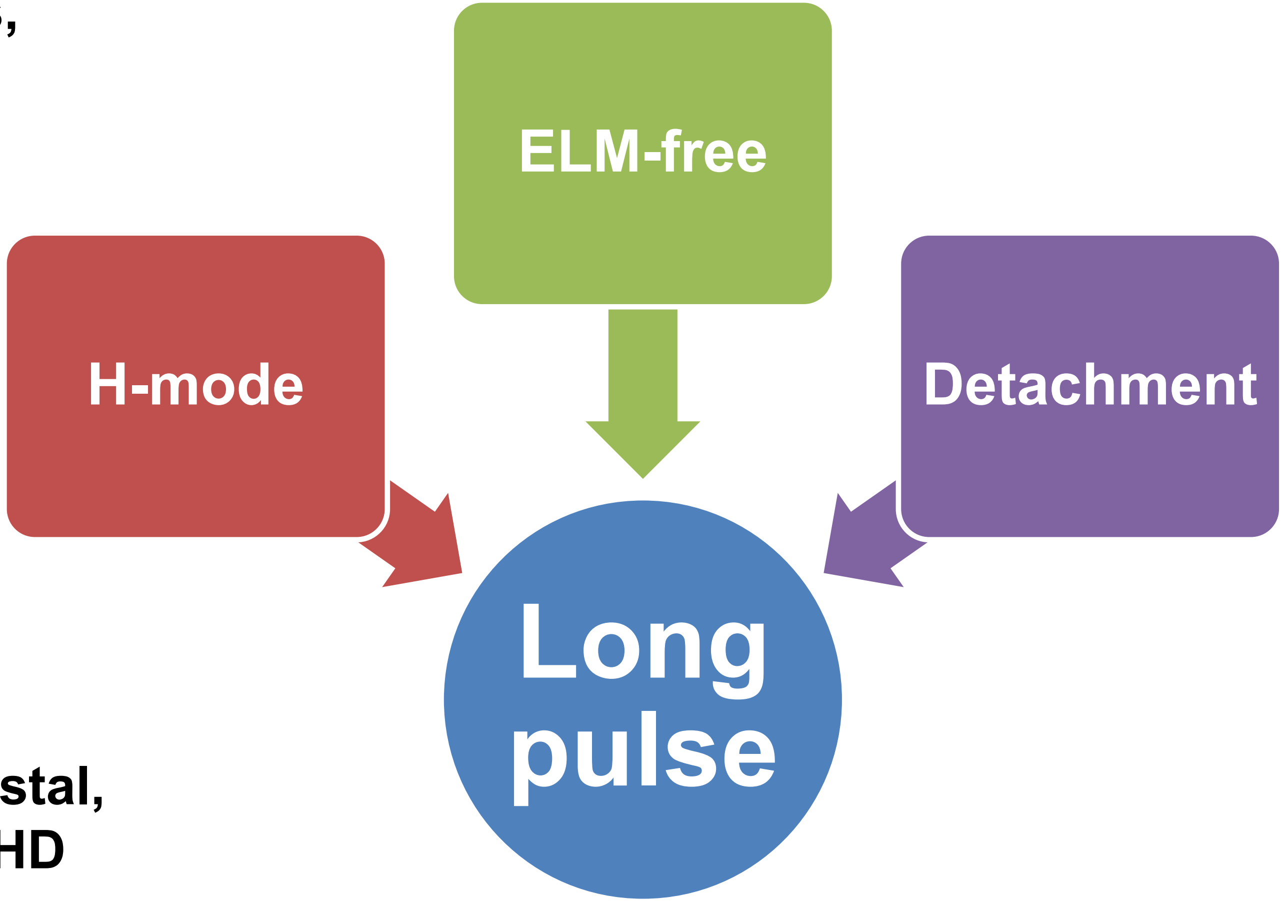
- Introduction
- ELM-free H-mode with divertor detachment via feedback-controlled N_2 seeding
- Pedestal turbulence and gyrokinetic simulations
- Gyrokinetic simulation of ITER pedestal modes
- Summary

Stationary detached ELM-free H-mode is a desirable plasma regime for metal wall as metallic impurity source can be reduced

- **Large ELMs pose a critical threat to the PFCs, which generate metallic impurities that contaminate the core plasma, making stable operation of H-mode plasmas very difficult, especially in a full metal wall environment.**

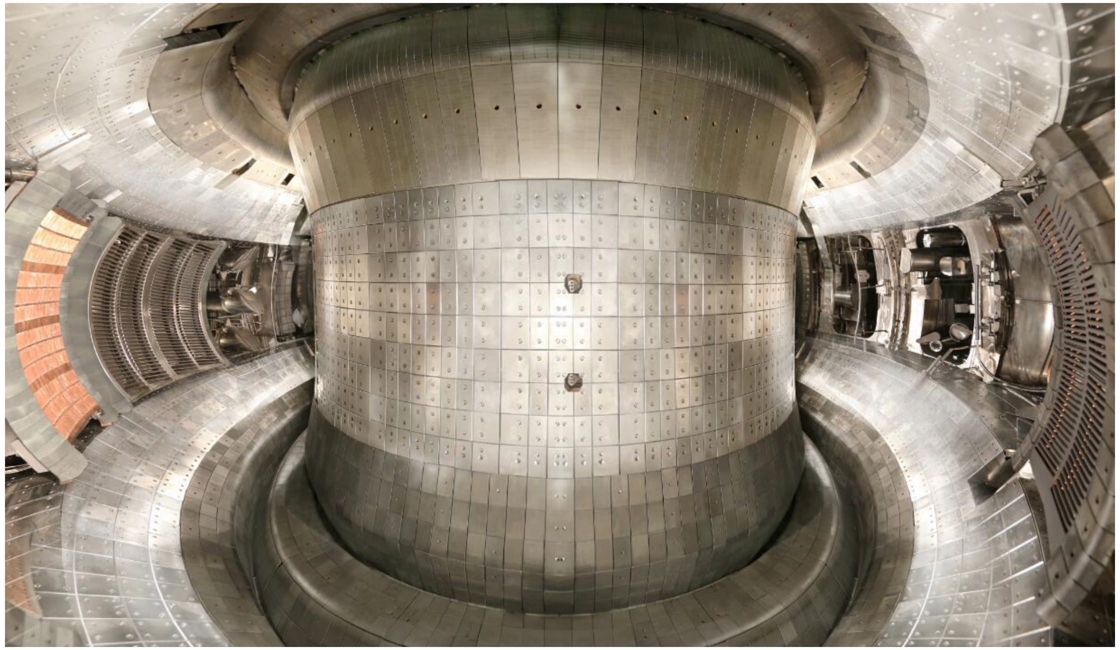
- **Therefore, a long-pulse stationary detached ELM-free H-mode with good energy confinement is a desirable plasma regime.**

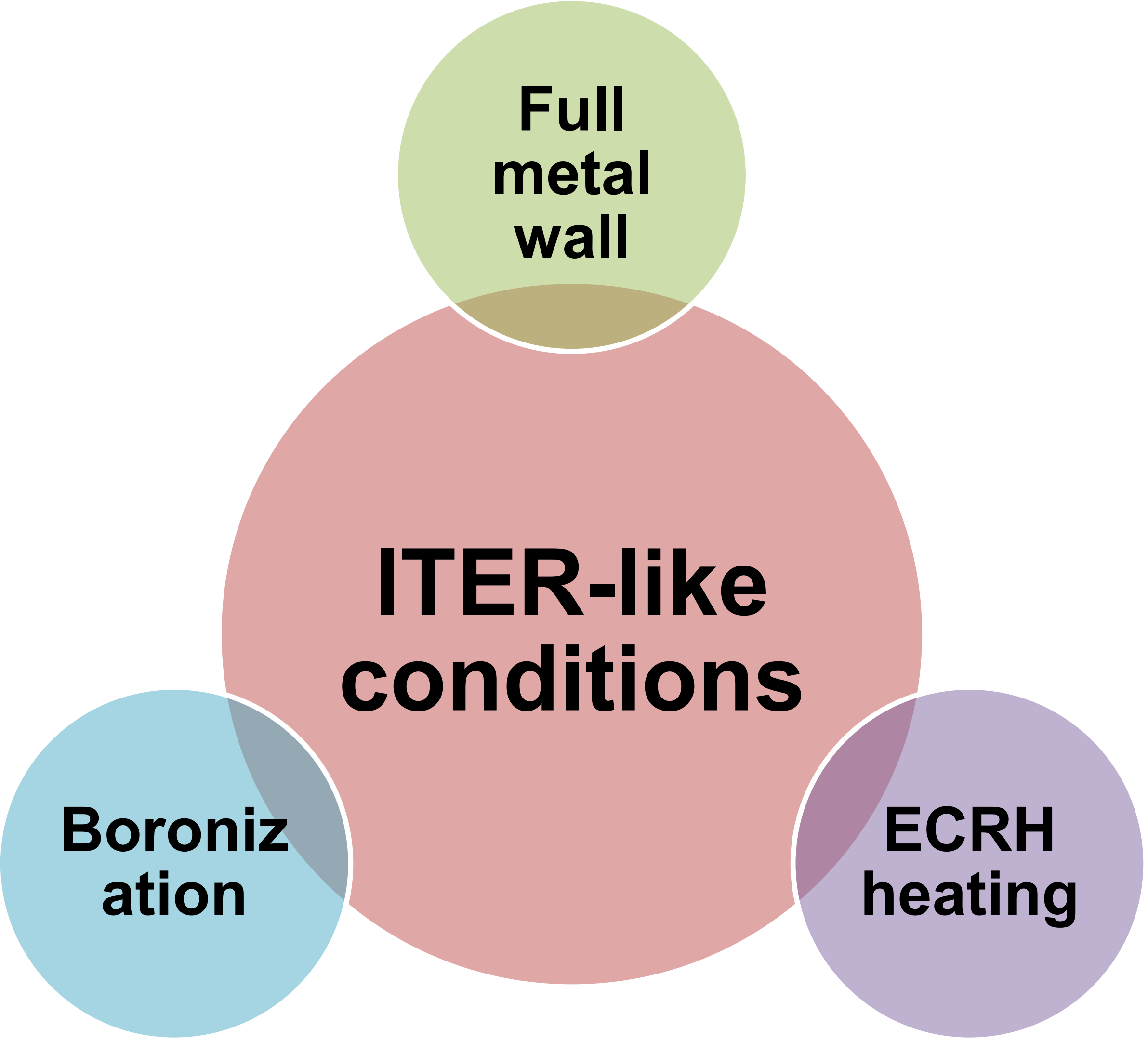
- **The key to access to this regime usually requires a transport channel across the pedestal, limiting the growth of pedestal beyond the MHD stability boundary to avoid ELMs. Turbulence can provide such a transport channel.**



Dedicated EAST experiments provide timely information for the consideration of switching the first wall of ITER to tungsten

- **EAST now has ITER-like conditions, i.e., boronized full-metal wall and high-power ECRH heating.**





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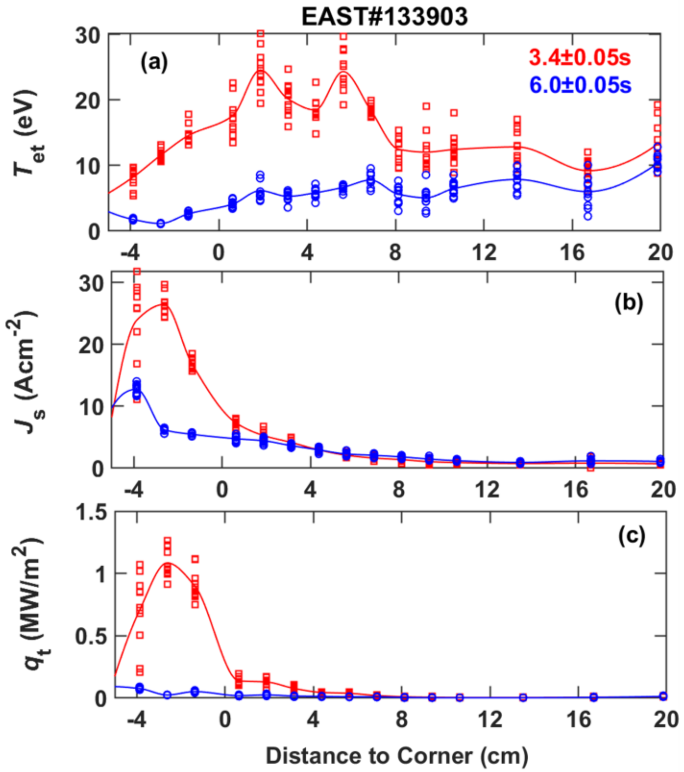
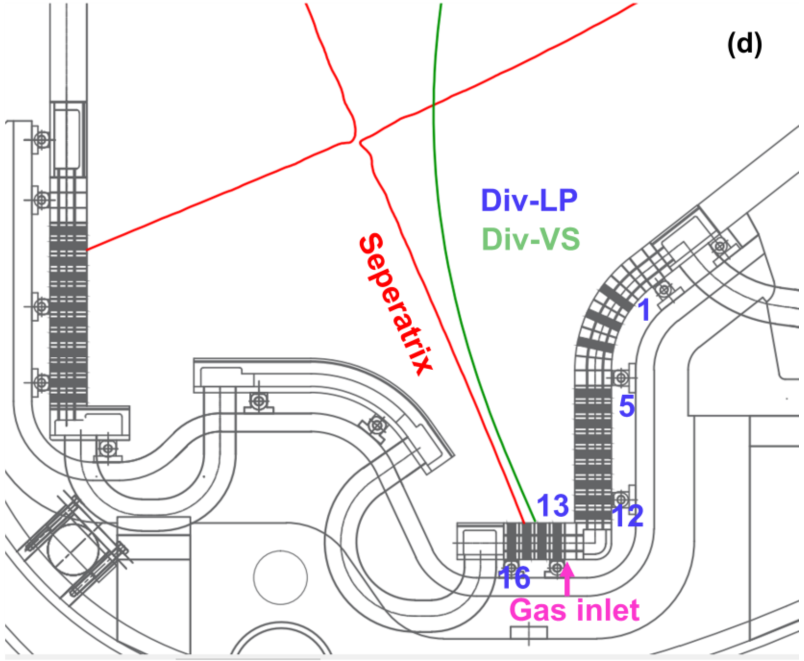
Divertor detachment by feedback control of T_{et} or AXUV radiation near the lower X point with seeding pulse width modulation



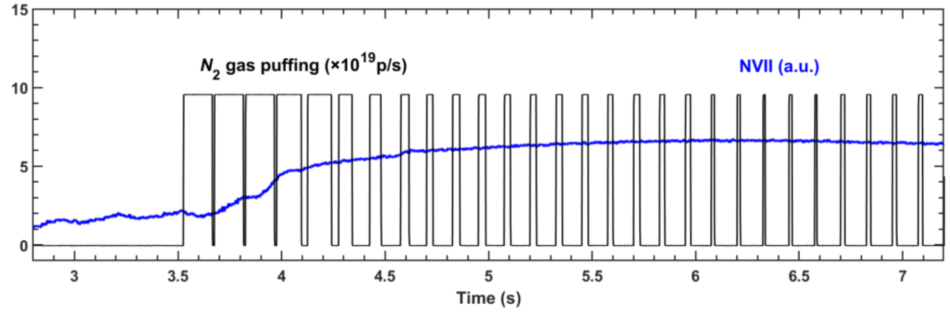
Profiles measured by divertor Langmuir probes

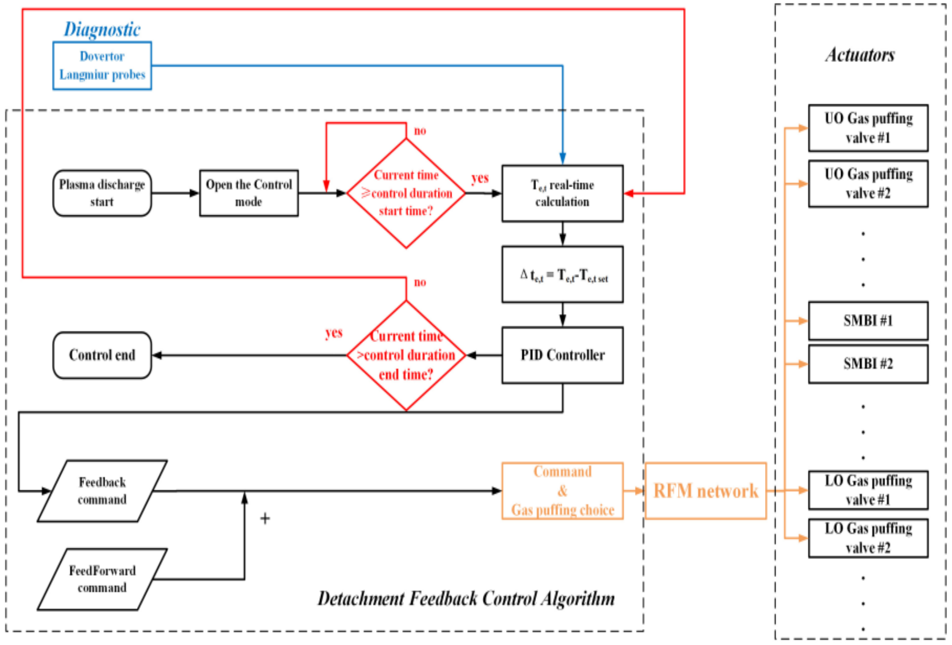
Partial detachment → T_{et} < 5eV near strike point



Divertor outer strike point was located on the horizontal target plate.

Nitrogen gas was injected from the horizontal target plate near the right-angle closed corner into the SOL.





Feedback control logic in PCS system

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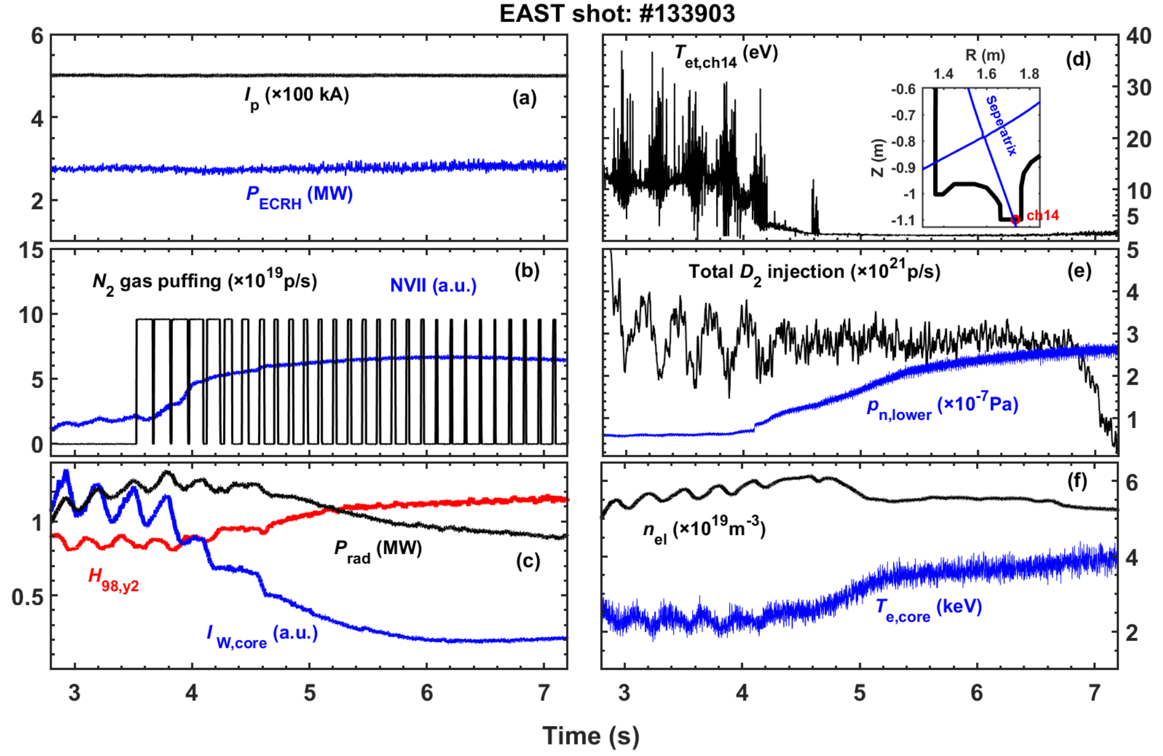
The detached ELM-free H-mode was first obtained at q_{95}=5.2 with H_{98y2} up to 1.2 in short pulses

- P_{EC}~2.8MW =1.3-1.8 $P_{L\text{-}H}$
- β_N ~1.40, β_P~1.39, l_i~1.1, q_0~1, κ~1.7, δ_l~0.59, no ITB
- LSN configuration with dR_{sep}~-4 mm
- Plasma-limiter-surface outer gap dR_{out}~7.3 cm



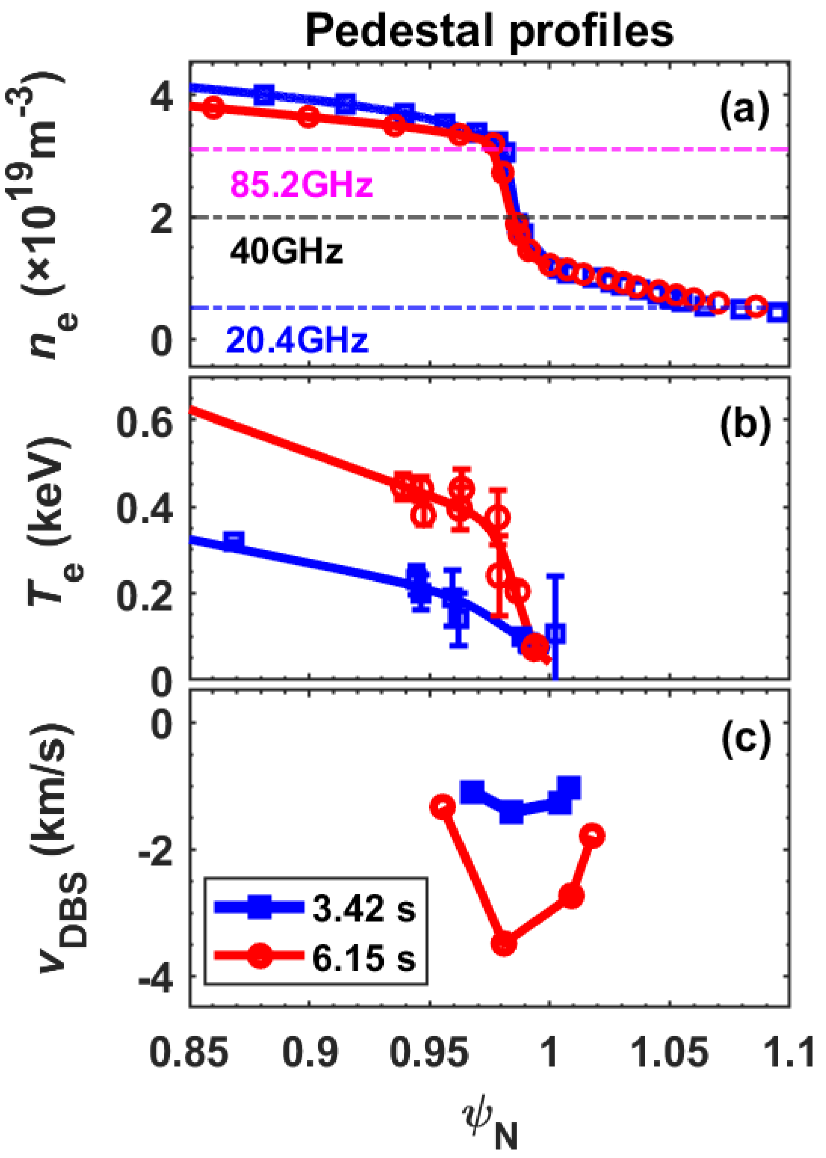
- **Prior to N_2 seeding, large ELMs appeared intermittently.**
- **ELMs were completely suppressed when divertor detachment was achieved at the lower outer divertor.**
- **Divertor neutral pressure significantly increased with divertor detachment, which enhances the pumping of recycling neutral particles and reduce the fueling of the pedestal, while the external gas fueling rate remained nearly unchanged, so that the density of main plasma decreased and the electron temperature significantly increased.**
- **W_{MHD} and H_{98y2} increased accordingly.**
- **Metal impurity radiations of tungsten, molybdenum, copper and iron in the plasma core region were significantly reduced, which could be a result of suppression of impurity source.**

Pedestal profile changes

- With N_2 seeding, n_e at the top of the pedestal rose at first prior to divertor detachment due to impurity ionization, and then continued to decrease during divertor detachment, due to reduced fueling from the recycling neutral particles.

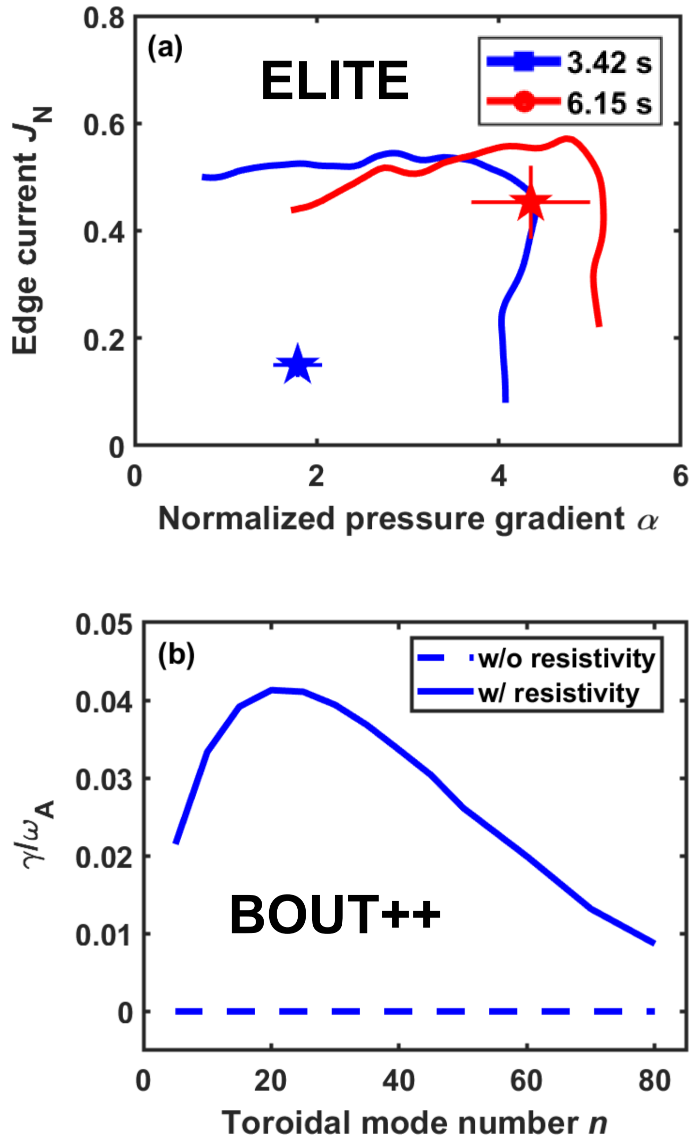
- Meanwhile, T_e at the top of the pedestal nearly doubled with a significant increase in the pedestal T_e gradient, which may be responsible for the enhanced energy confinement.

- Poloidal velocity in the pedestal region measured by DBS diagnostic becomes much more negative in the electron diamagnetic direction, which may suggest a significant increase in the ExB velocity shear.



Linear stability analysis of the pedestal Peeling-Ballooning modes using ELITE and BOUT++ codes

- Prior to N_2 seeding, ELITE analysis indicates that the pedestal is in the deeply stable region of the ideal PB modes.
- During N_2 seeding, the pedestal is still in the stable region, but getting closer to the corner between the peeling boundary and the ballooning boundary.
- BOUT++ simulations suggest that when the effects of resistivity are taken into account, even though the pedestal is in the deeply stable region of the ideal PB modes, the resistive PB modes are still unstable, which may explain why ELMs still appeared intermittently prior to N_2 seeding in the experiment.

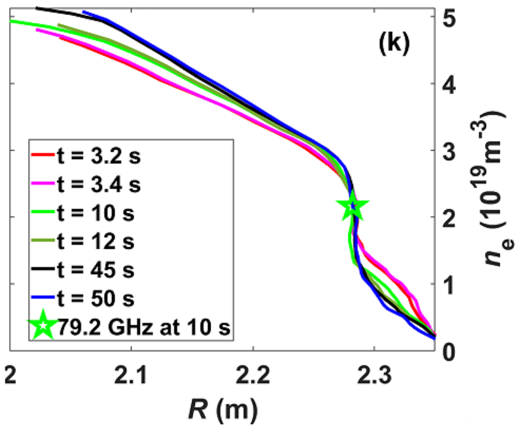


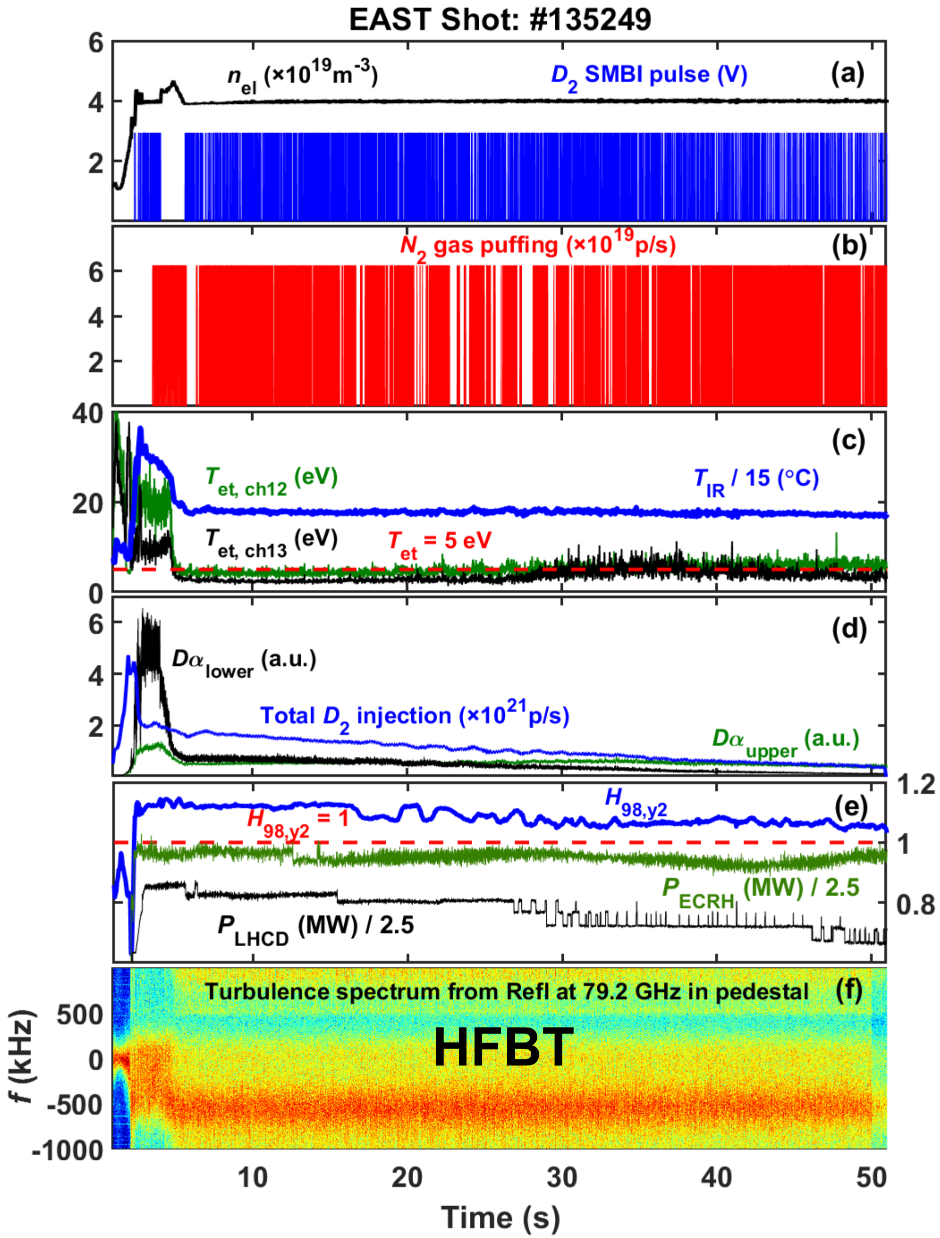
>50s long-pulse ELM-free H-mode with feedback-controlled divertor detachment under boronized metal wall in EAST

- Stable detachment at both the inner and outer target plates of the lower divertor was achieved. T_{et}~2eV and the divertor peak surface temperature measured by an infrared camera was reduced from ~500℃ to ~250℃;

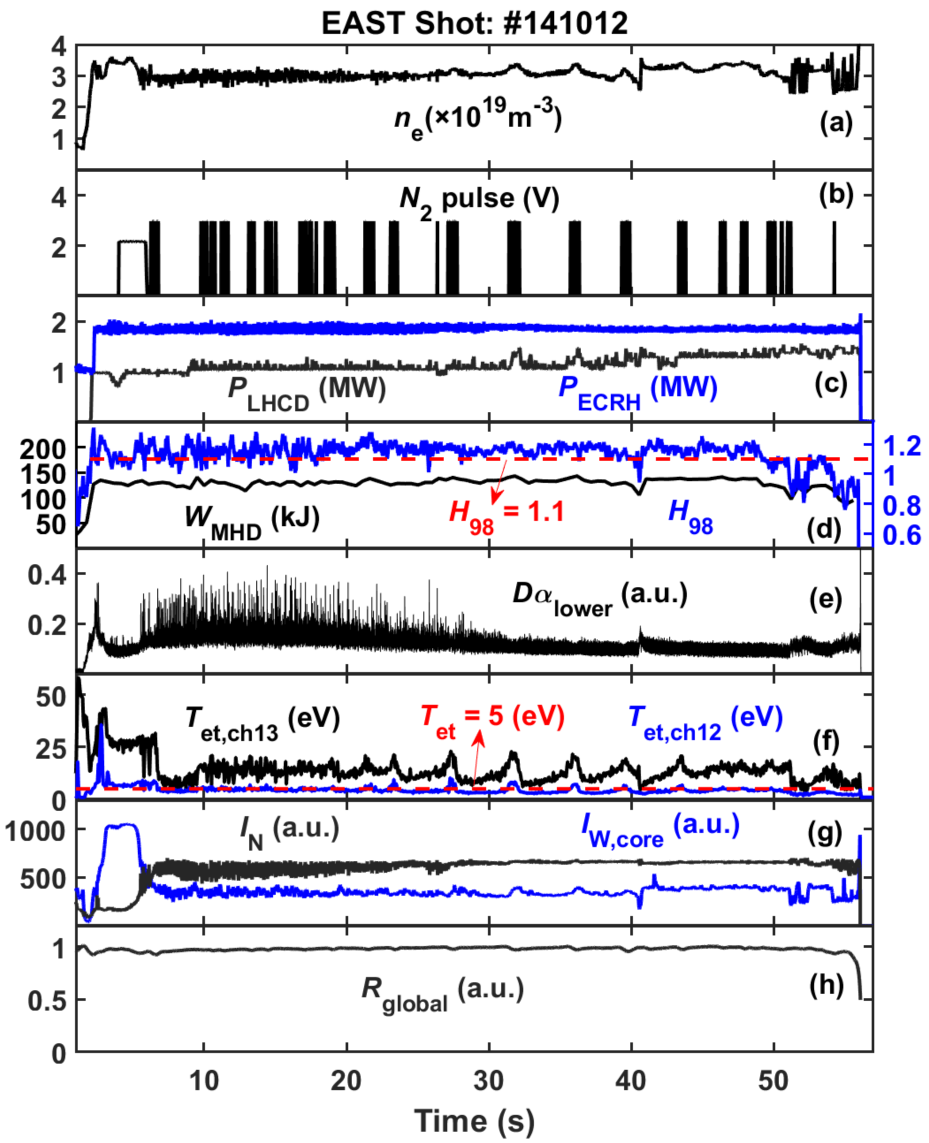
- Divertor Dα drops sharply when N_2 seeding begins and then continues to decrease. At the same time, n_e in the SOL significantly decreases;

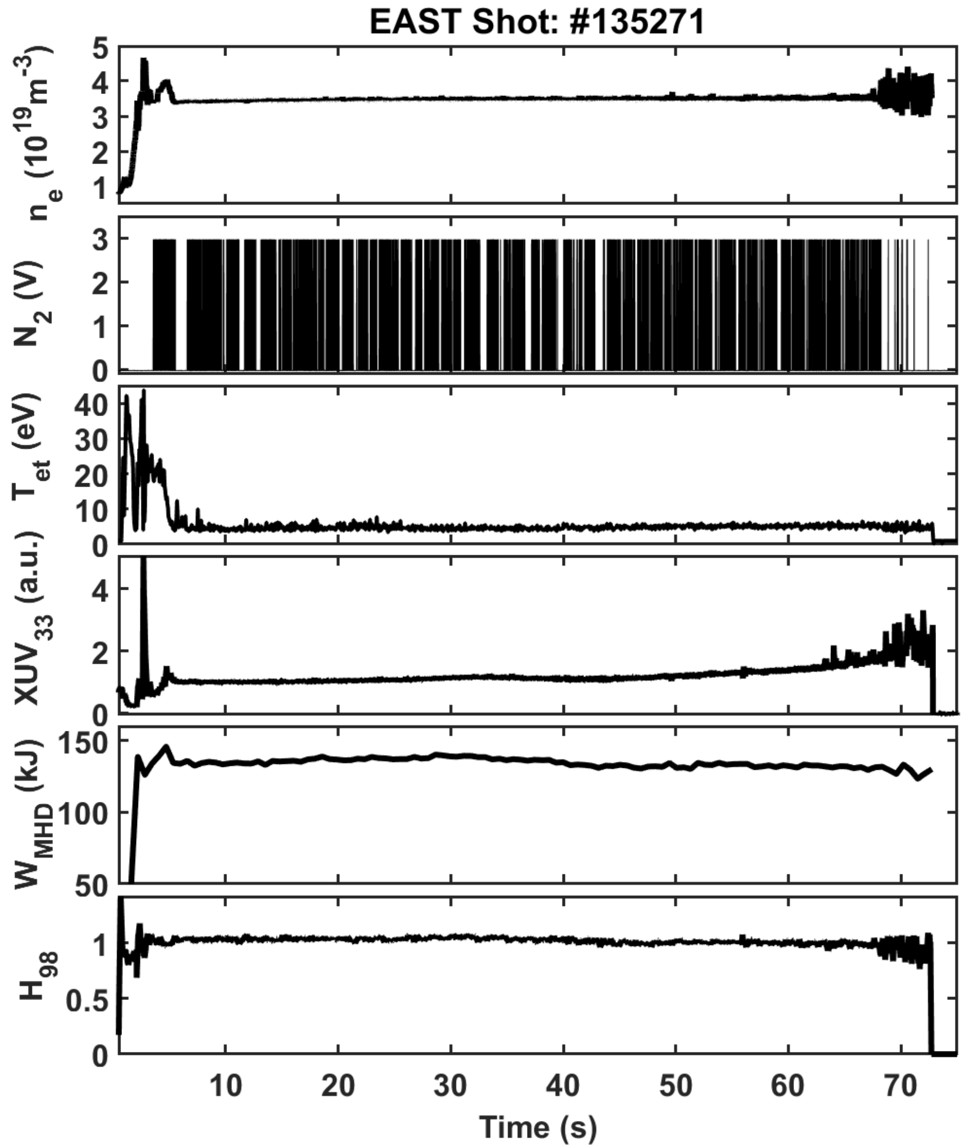
- This may be because at the onset of divertor detachment the power flow to the divertor is significantly reduced, resulting in less ionization of recycling neutral particles due to the so-called 'power starvation' effect.





With I_p reduced to 350 kA, ~70 s long-pulse stationary detached ELM-free H-mode plasma obtained at q_{95}=6.8





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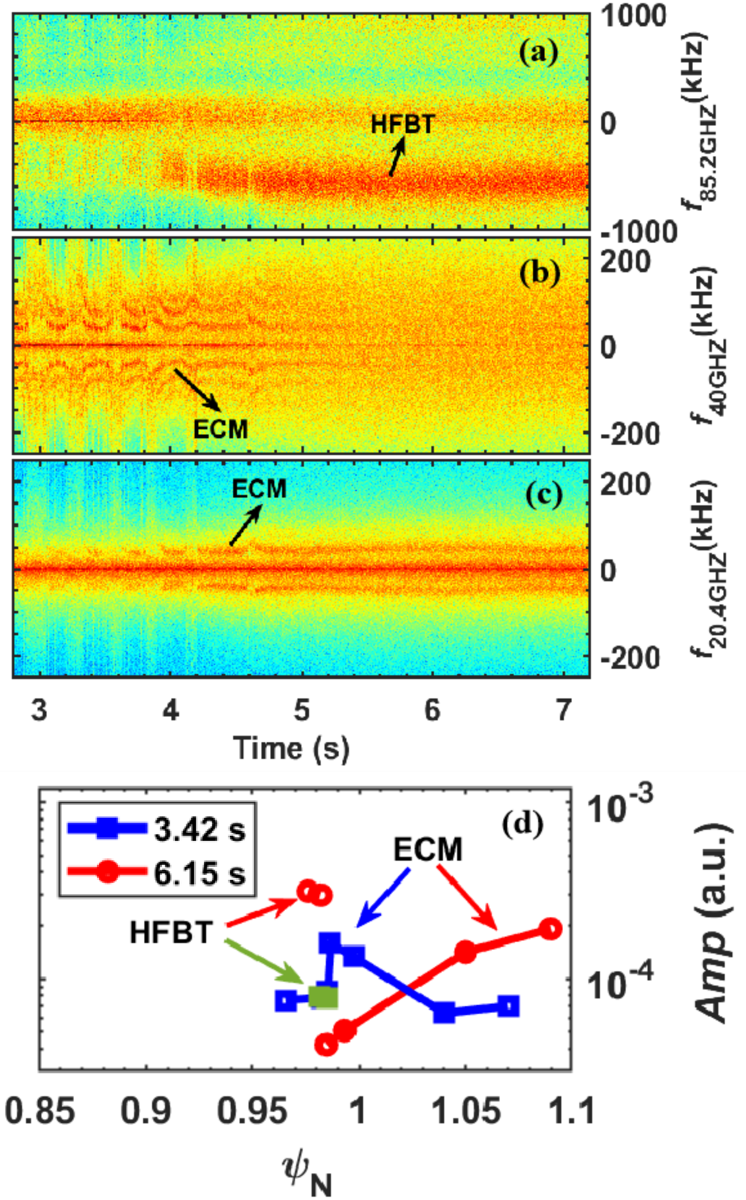
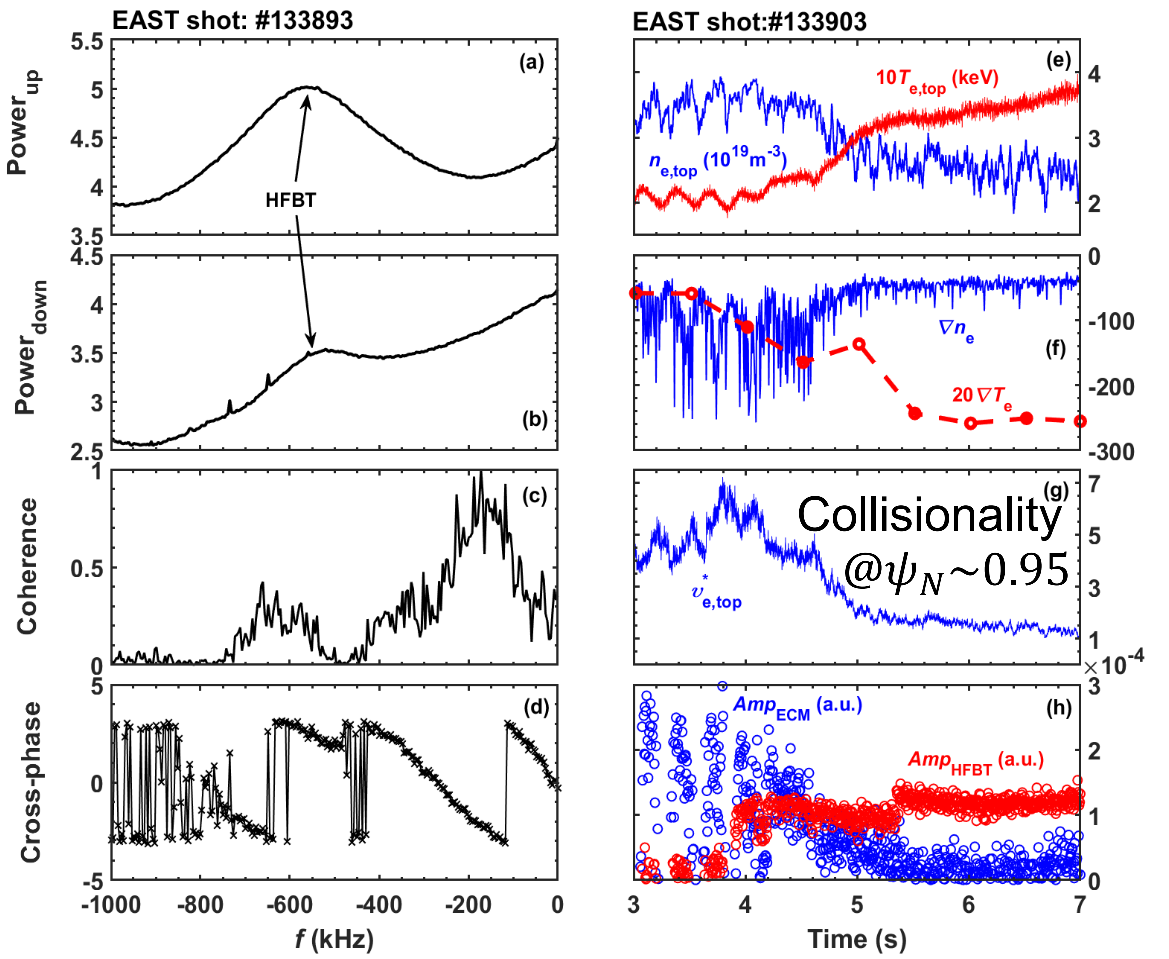
Pedestal turbulence behavior

- Before N_2 seeding, a High Frequency Broadband Turbulence (HFBT) appeared in the upper region of the pedestal with a frequency of about 200-500 kHz. During N_2 seeding, the HFBT becomes stronger and its frequency upshifts to 400-700 kHz.
- It was not visible to the high-frequency Mirnov coils, suggesting that it could be an electrostatic mode.
- In the lower region of the pedestal and in the SOL, a quasi-coherent mode at a frequency of ~40 kHz with multiple harmonics also appeared in the ELM-free periods, which is the Edge Coherent Mode (ECM), usually seen in the EAST H-mode pedestal region at high collisionality, which was identified as Dissipative Trapped Electron Mode (DTEM).
- With divertor detachment, the amplitude peak of ECM moves outward from the pedestal steep-gradient region to the SOL.



Experimental characterization of HFBT

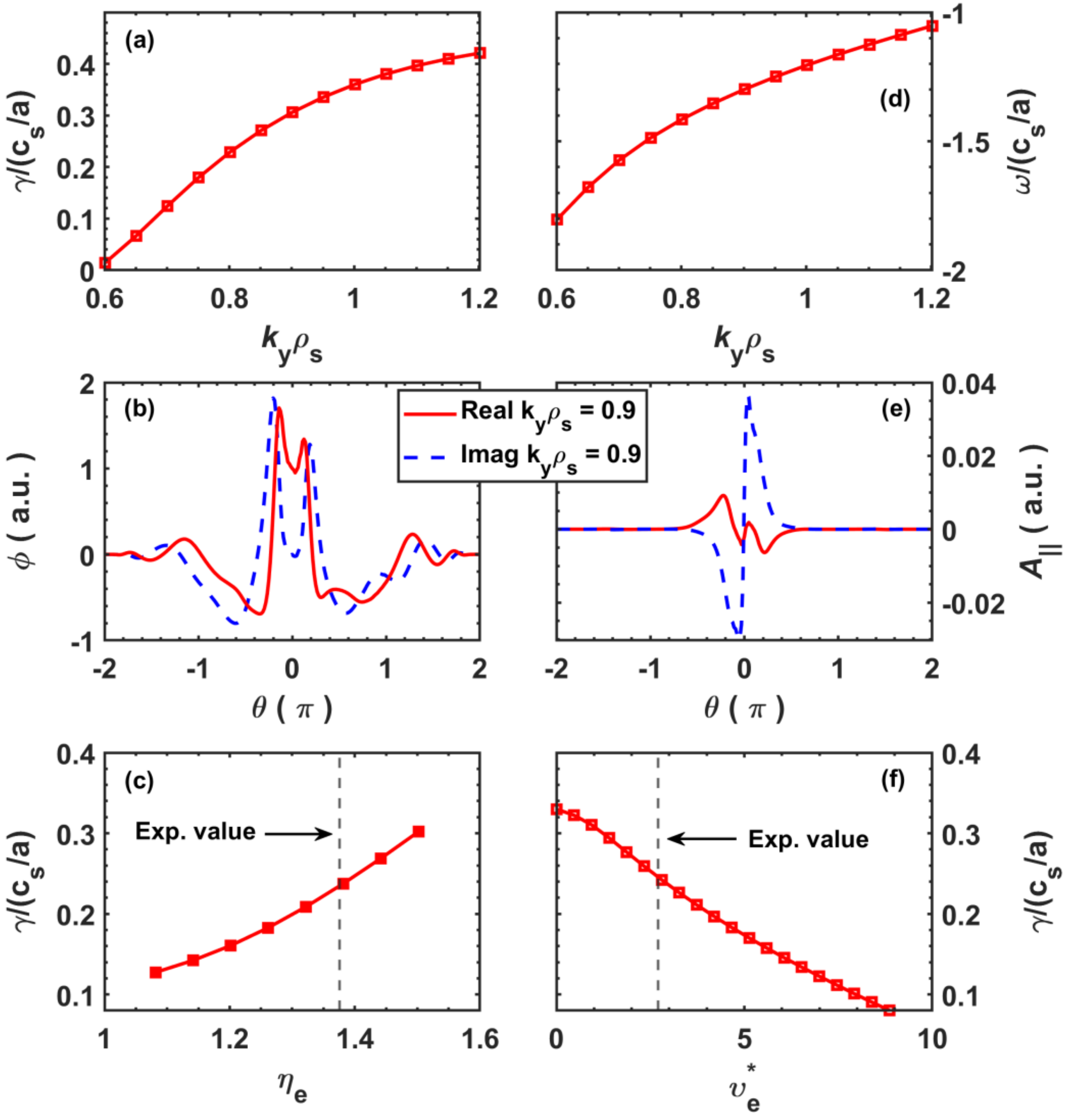
- **HFBT propagates in the Electron Diamagnetic Drift (EDD) direction in the laboratory frame;**
- **Poloidal correlation reflectometer measurements indicate the poloidal wave number of HFBT $k_y=(3.11+2\pi)/16\sim0.59\ mm^{-1}$, and $k_y\rho_s\sim0.85$;**
- **From the parameter time evolution, we can see the amplitude of HFBT increases with the increase of the pedestal electron temperature gradient and the decrease of the pedestal top collisionality;**
- **The HFBT has also be observed in the EAST experiments with much lower pedestal collisionality ($\nu^*_{e,top}<1$).**



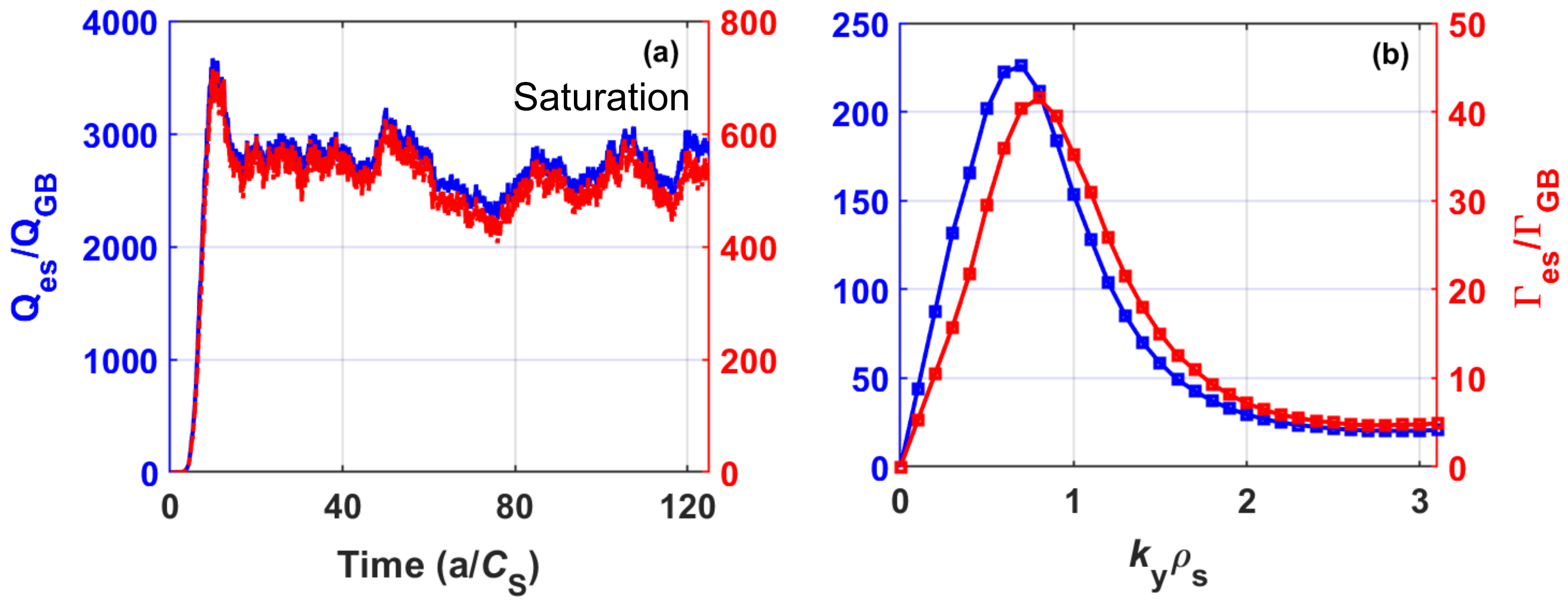
Poloidal correlation reflectometer array measurements

Linear gyrokinetic simulations with GENE code

- During N_2 seeding, in the range $k_y\rho_s$=0.6-1.2, there is a mode in the EDD direction with a real frequency of f ~ 100 kHz.
- Frequency in the laboratory frame $f_{lab} = f + f_{E\times B}$ ~ 500 kHz, where $f_{E\times B} = nE_r / (2\pi RB_\theta)$ ~ 400 kHz, $n = k_y r / q$ ~ 54, consistent with the experimental observation of HFBT.
- η_e scan and collisionality scan indicate that the mode is destabilized by electron temperature gradient and stabilized by collisionality.
- The electrostatic potential features an even-parity structure. The parallel magnetic vector potential features an odd-parity structure with a much lower amplitude compared with that of the electrostatic potential.
- These characteristics suggest that this mode is η_e-TEM, consistent with the experimental observations of HFBT quite well.



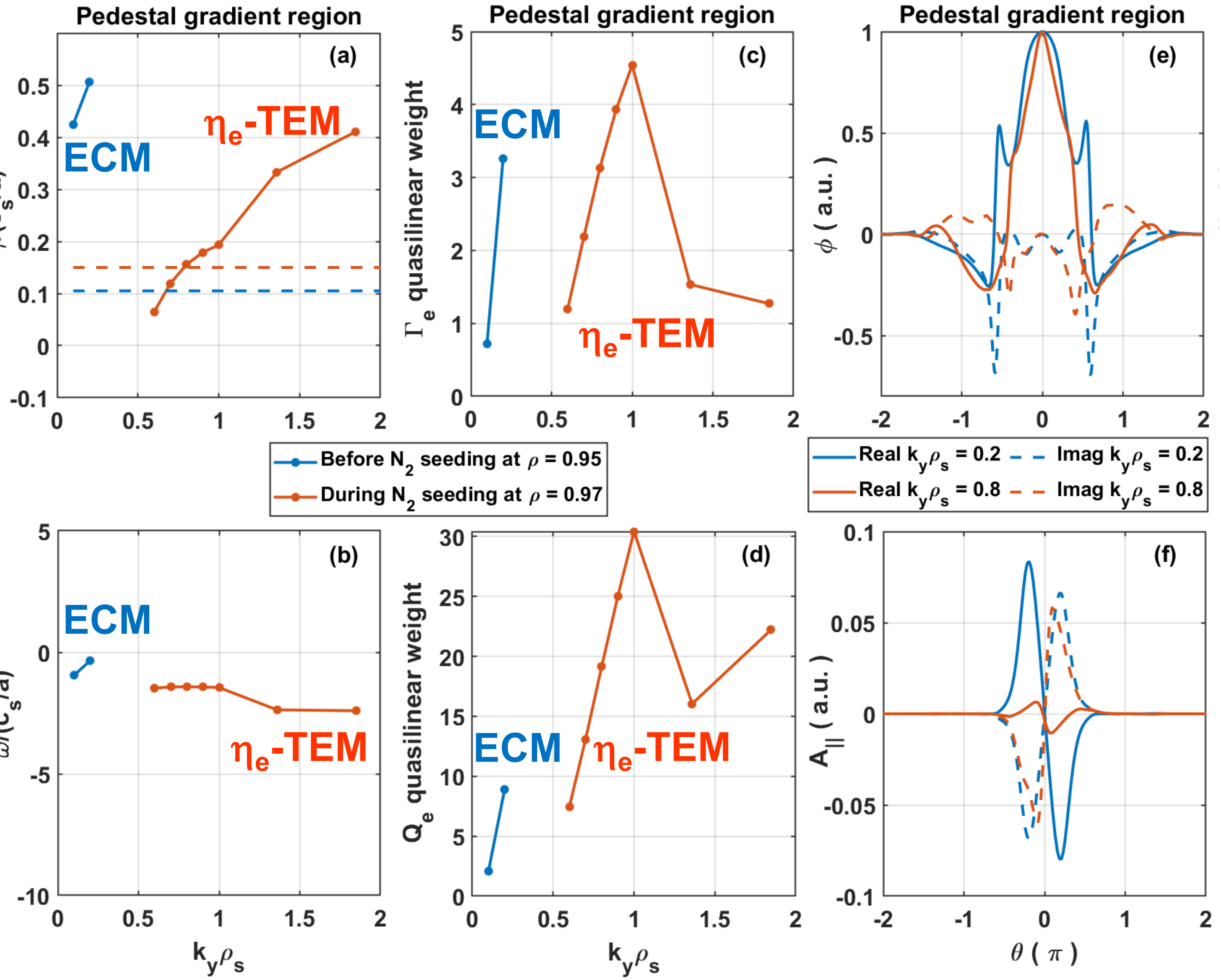
Nonlinear gyrokinetic simulations with GENE code



- **Nonlinear flux spectra suggests that η_e-TEM dominates the fluxes, driving significant outward electrostatic particle and electron heat fluxes;**
- **The fluxes peak at $k_y\rho_s$~0.85, consistent with the experimental observation of HFBT.**

Linear gyrokinetic simulations with CGYRO code

- **Before N_2 seeding, the simulations show a low-frequency mode in the low $k_y \rho_s$=0.1-0.2 range, consistent with the characteristics of the ECM seen in the experiments.**
- **During N_2 seeding, the simulations show η_e-TEM ($k_y \rho_s$=0.6-3.4) in the pedestal gradient region with the linear growth rate exceeding the local ExB shear rate, which is destabilized by electron temperature gradients, consistent with the experimental observations.**
- **This mode drives radially outward particle and electron heat fluxes.**



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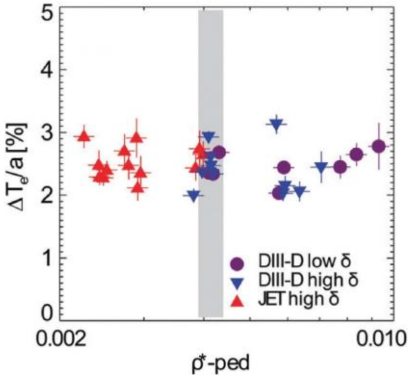
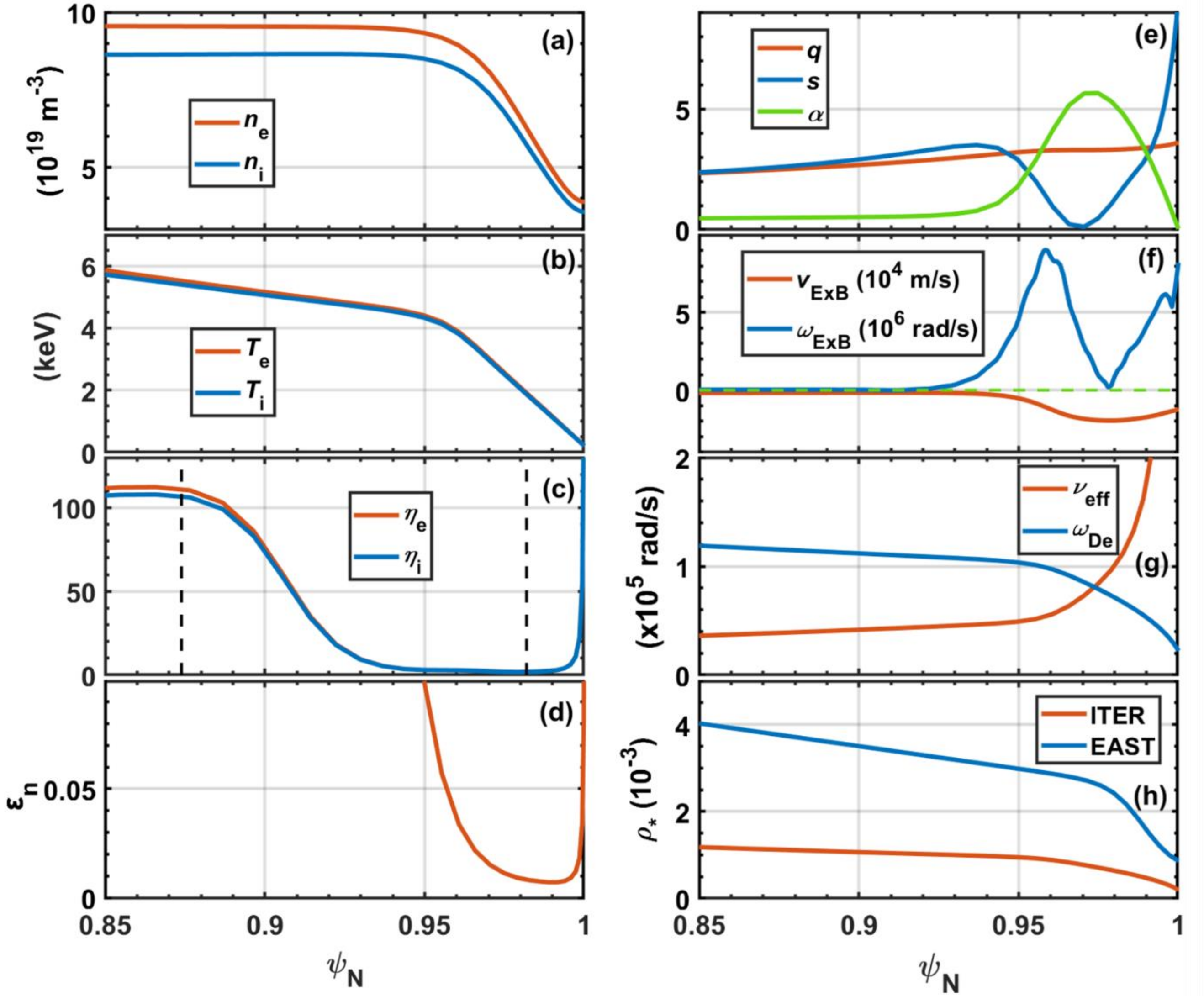
ITER Ip=15MA baseline scenario generated by CORSICA integrated modeling code with the pedestal based on EPED

- **In ITER and future fusion reactors, the normalized ion gyroradius, $\rho_* = \rho_i / a$, in the pedestal region is expected to be approximately 3 times smaller than that in present tokamaks.**
- **Turbulence suppression by ExB flow shear is predicted to scale with ρ_*, as $\omega_{ExB}/\gamma_{lin} \propto (a/w)\rho_*$**
- **Multi-device experiments of ρ_* scans indicate that the relative pedestal width w/a is independent of ρ_*.**



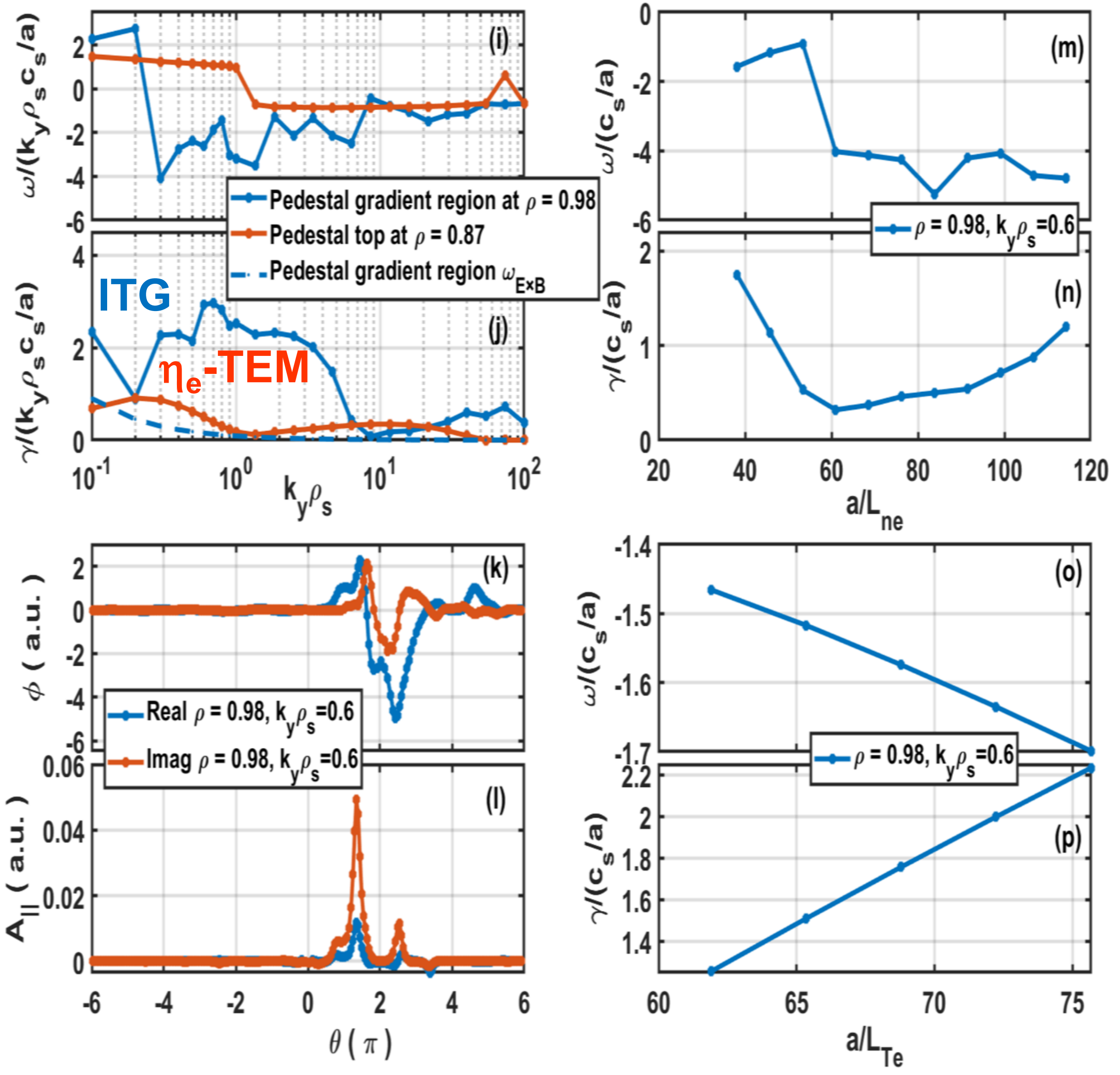
- **Therefore, the turbulence suppression in ITER pedestal is expected to be significantly weaker, and thus the ITER pedestal region would be more prone to low-k and intermediate-k turbulences, particularly ITG and TEM turbulences, which are usually suppressed by strong ExB flow shear in the pedestal of present tokamaks.**



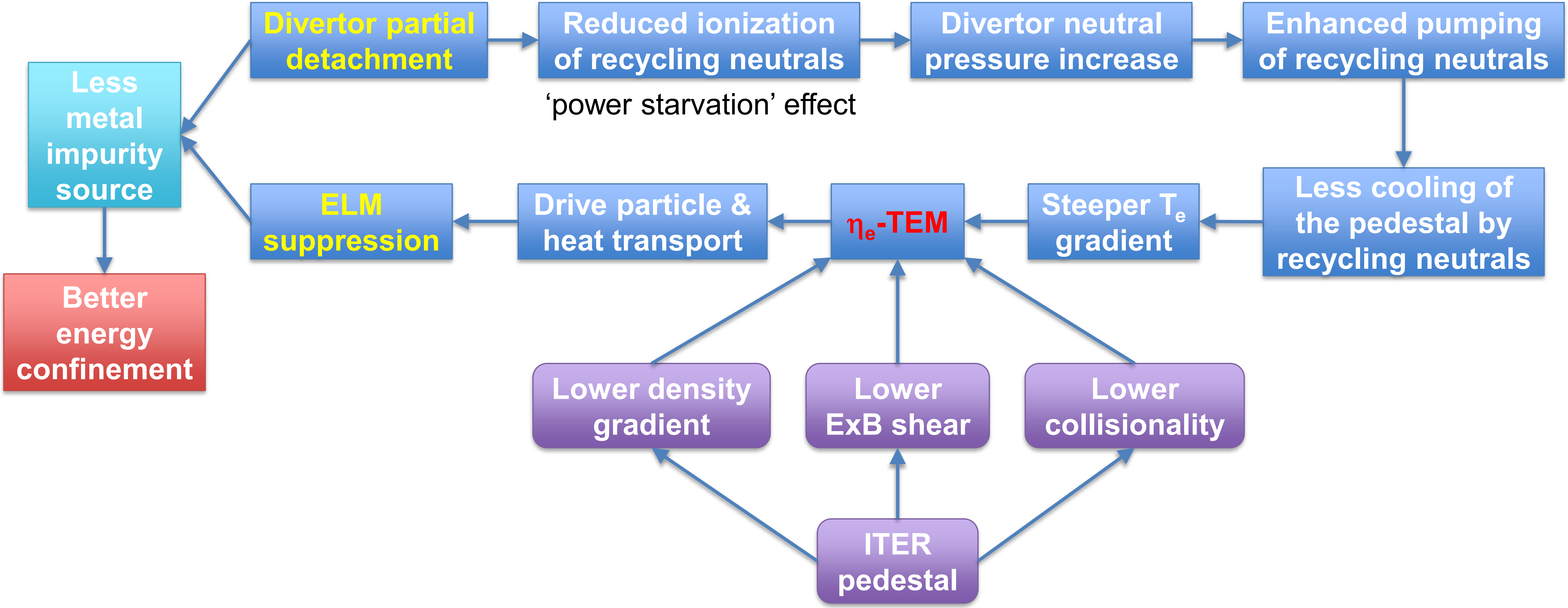
[1] M. Kotschenreuther, et al. Nucl. Fusion 57, 064001 (2017).
[2] D. R. Ernst et al., (IAEA, Vienna, 2018), paper IAEA-CN-258/EX/2-2

CGYRO simulations show η_e-TEM and ITG in the pedestal gradient region of ITER Ip=15MA baseline scenario

- **CGYRO simulations show η_e-TEM and ITG in the pedestal gradient region with their linear growth rates well above the local ExB shear rate.**
- **ITG and ETG appear at the pedestal top where η_i and η_e are large due to low density gradient.**
- **In the low q_{95} parameter region of the ITER baseline scenario, present-day tokamaks typically experience large ELMs and strong suppression of turbulence by ExB shear. However, our simulations suggest that the pedestal region of the ITER baseline scenario could be dominated by turbulence which may lead to the suppression of ELMs.**



Principle for turbulence-dominated pedestal in detached H-mode plasma and prospects for future fusion reactors



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Summary

- >50s long-pulse high-performance ELM-free H-mode regime has been achieved in EAST with feedback-controlled divertor detachment under boronized full-metal wall and high-power ECRH heating and LH current drive.
- Divertor detachment leads to an enhanced pumping and reduced ionization of recycling neutrals in the divertor and a significant increase of pedestal electron temperature gradient, which in turn excites a HFBT in the pedestal gradient region.
- Gyrokinetic simulations with GENE and CGYRO codes suggest the HFBT being η_e-TEM, driving outward particle and electron heat transport, which can be excited in the low-collisionality pedestal of ITER and future fusion reactors.
- The expected lower density gradient, ExB shear and collisionality in the ITER pedestal will even facilitate the excitation of η_e-TEM, making this pedestal regime a potential candidate in ITER.

Thank You