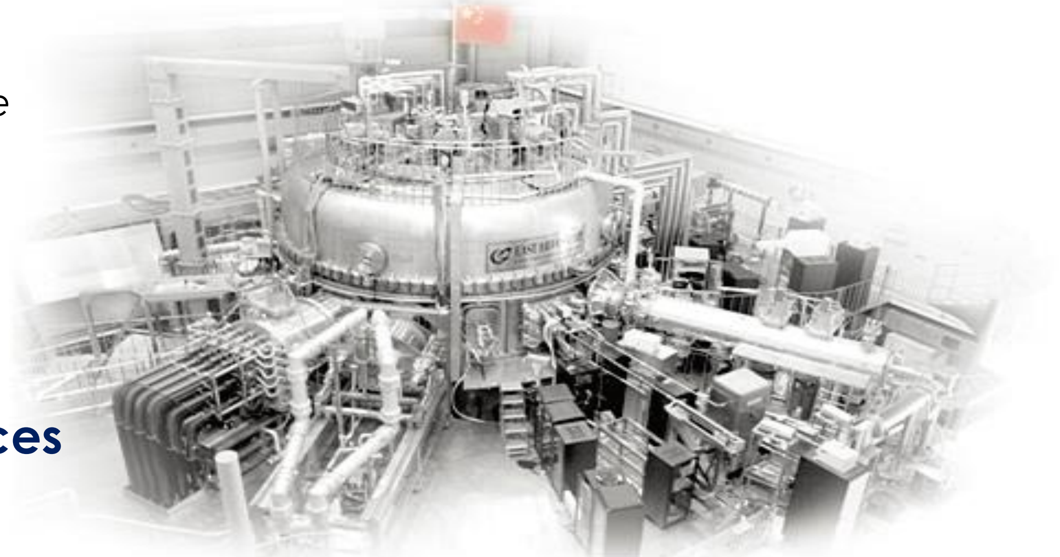
Long-pulse no-ELM H-mode operation with feedback-controlled detachment and H_{98y2}~1.1 under boronized metal wall in EAST

by

Guosheng Xu[1]*

G.F. Ding[1], X. Jian[1], Y.F. Wang[1], H.Y. Guo[2], T. Zhang[1], K. Wu[1], K.D. Li[1], Q.Q. Yang[1], R. Chen[1], L. Yu[1], L.Y. Meng[1], L. Wang[1], H.Q. Wang[3], S.Y. Ding[3], N.M. Li[4], X.Q. Xu[4], N. Yan[1], L.Q. Xu[1], X. Lin[1], B. Zhang[1], J.P. Qian[1], T.F. Zhou[1], P. Li[1], C. Zhou[5], Q. Zang[1], H.Q. Liu[1], F. Ding[1], L. Zhang[1], Y.F. Jin[1], Y.M. Duan[1], Y.W. Yu[1], R. Ding[1], G.Q. Li[1], X.Z. Gong[1], K. Lu[1], J.S. Hu[1], Y.T. Song[1], B.N. Wan[1]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[2]College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[3]General Atomices, P. O. Box 85608, San Diego, CA 92186 5608, USA
[4]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[5]University of Science and Technology of China, Hefei 230026, China



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***E-mail: gsxu@ipp.ac.cn**

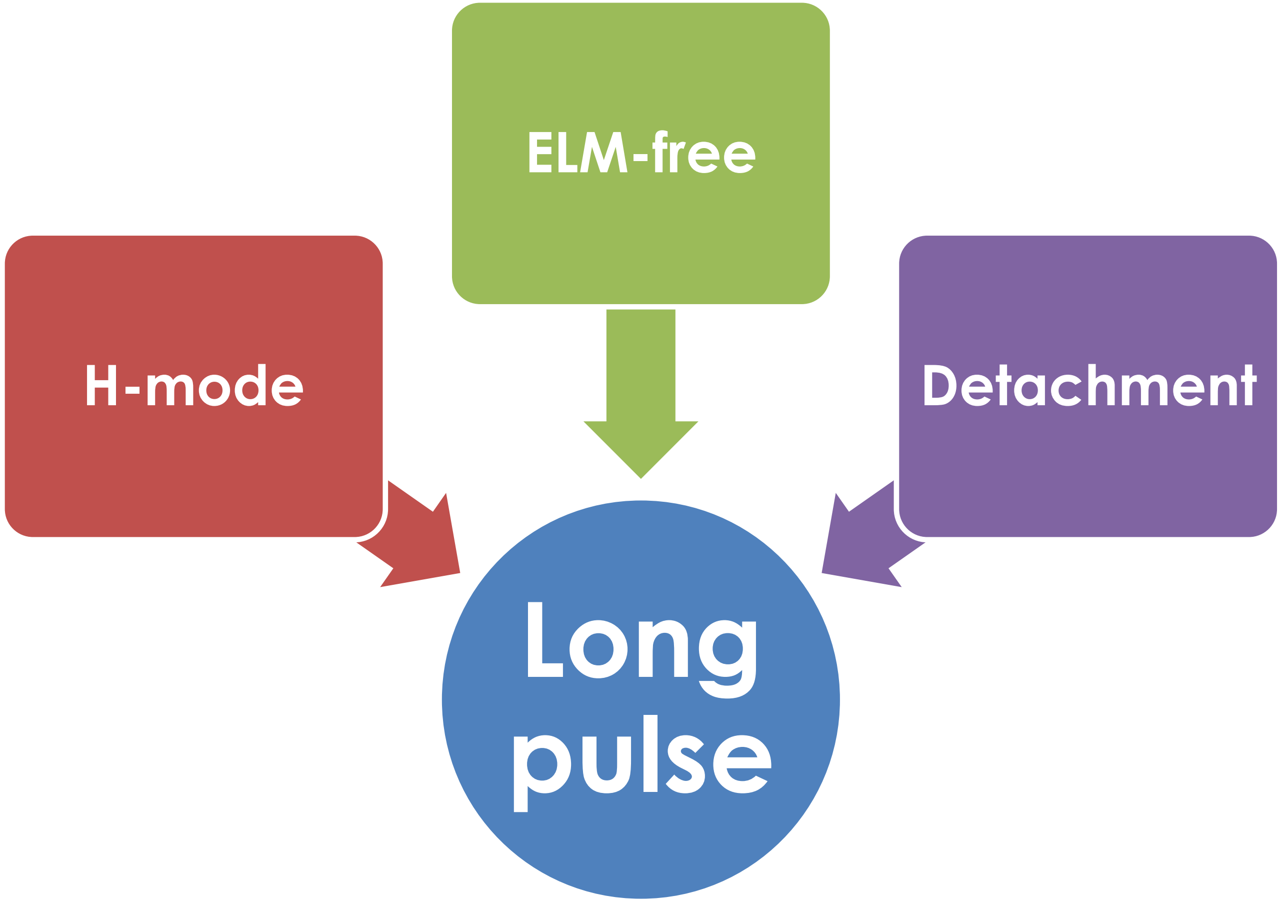
Outline

- Introduction
- Experimental results
- Simulation of EAST pedestal modes using CGYRO code
- Simulation of ITER pedestal modes using CGYRO code
- Summary

ASIPP

Stationary detached ELM-free H-mode is a desirable plasma regime for metal wall

- Large ELMs pose a critical threat to the PFCs, which generate metallic impurities that contaminate the core plasma, rendering stable H-mode operation difficult.
- Therefore, a long-pulse stationary H-mode regime without ELM but with good energy confinement, simultaneously coupled with divertor detachment is desirable.
- The key to its access usually requires a transport channel across pedestal to exhaust impurities and restricting the growth of the pedestal beyond the MHD stability boundary to avoid ELMs, especially in a metal wall environment.



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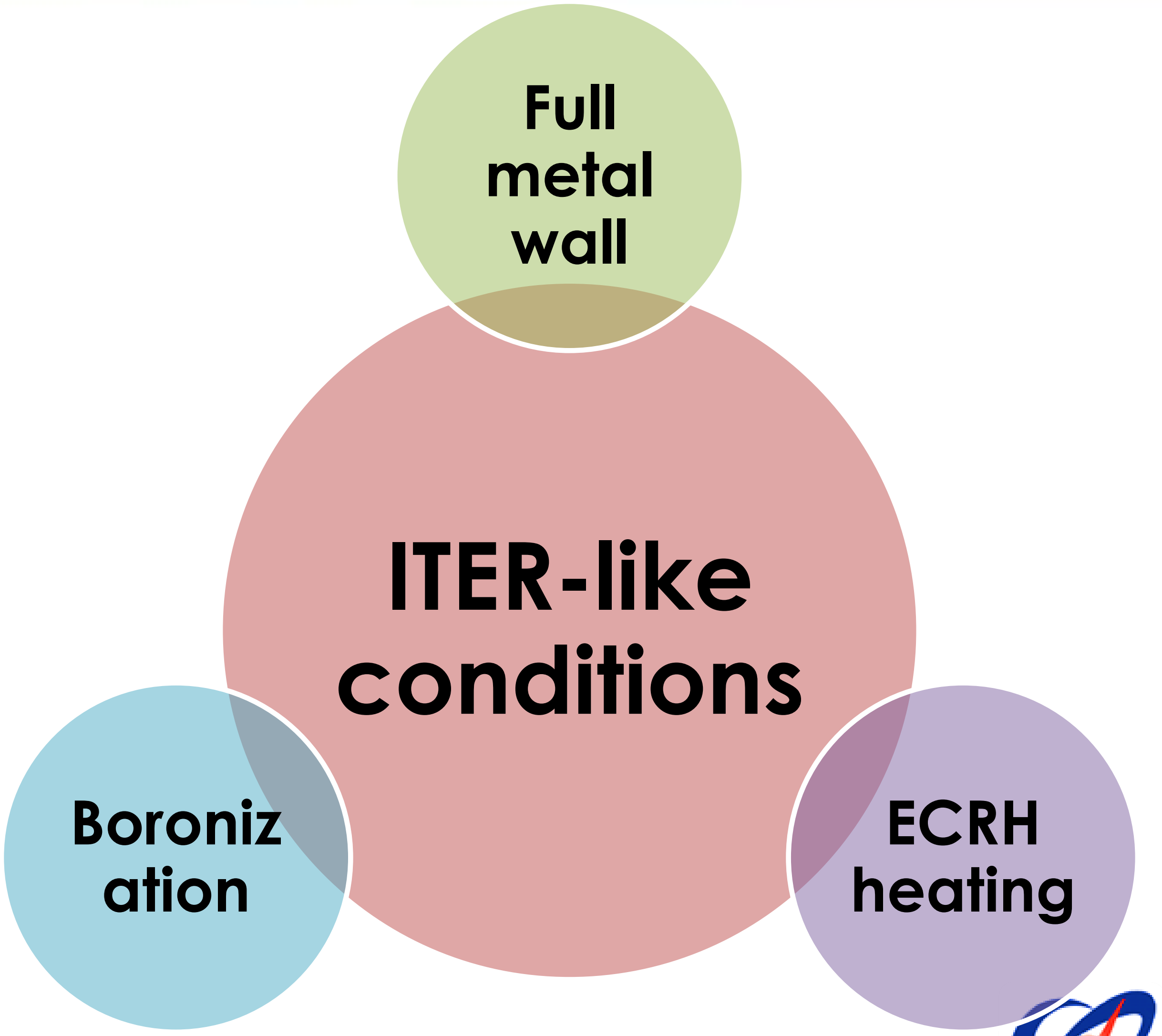
Dedicated EAST experiments provide timely information for the consideration of switching the first wall of ITER to tungsten

- **ITER is now considering switching its plasma-facing wall material from beryllium to tungsten, using boron to coat the wall, and using ECRH to control tungsten impurity concentration in the plasma.**

- **EAST now has ITER-like conditions, i.e., boronized full-metal wall and high-power ECRH heating. With boronization, nitrogen seeding can be applied.**

- **This experiment was carried out on the 4th day after the boronization with the evaporation of ~10g $C_2B_{10}H_{12}$ carbaborane solid. Following three days of high-power discharges, the boron film on the walls produced by boronization was nearly eroded away, resulting in essentially uncoated metal walls, similar to the situation for ITER, as the boron film will be eroded away much more quickly in ITER, leaving essentially uncoated metal walls.**



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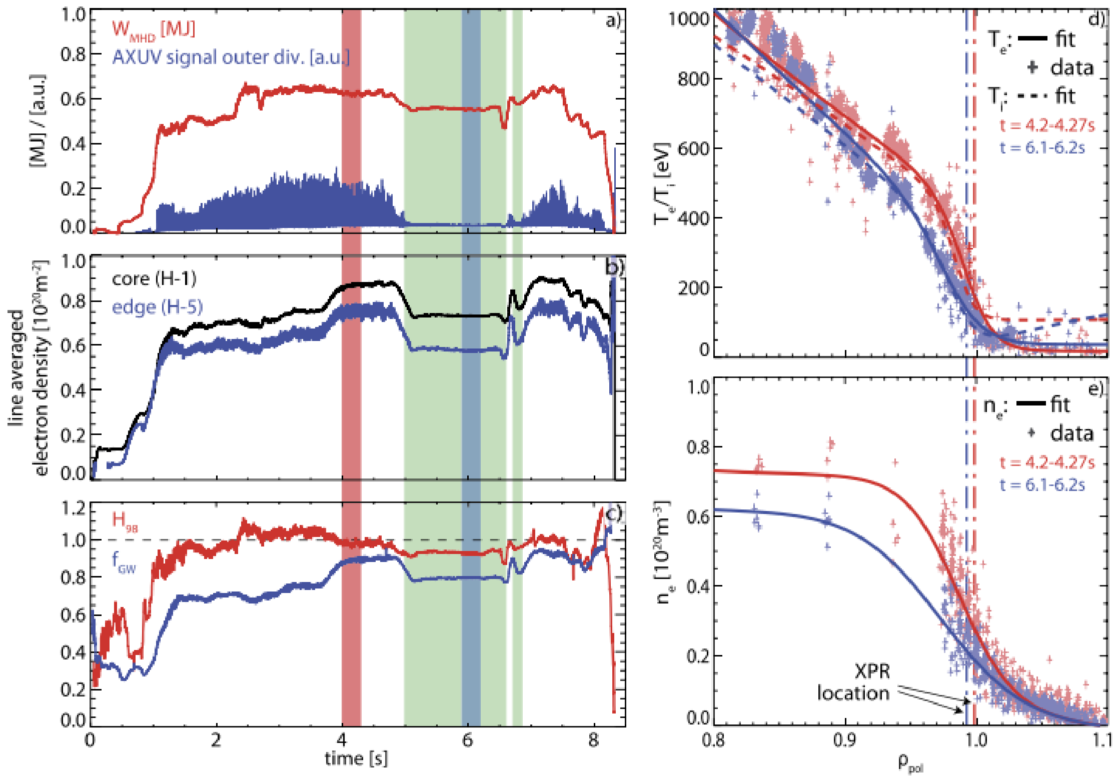
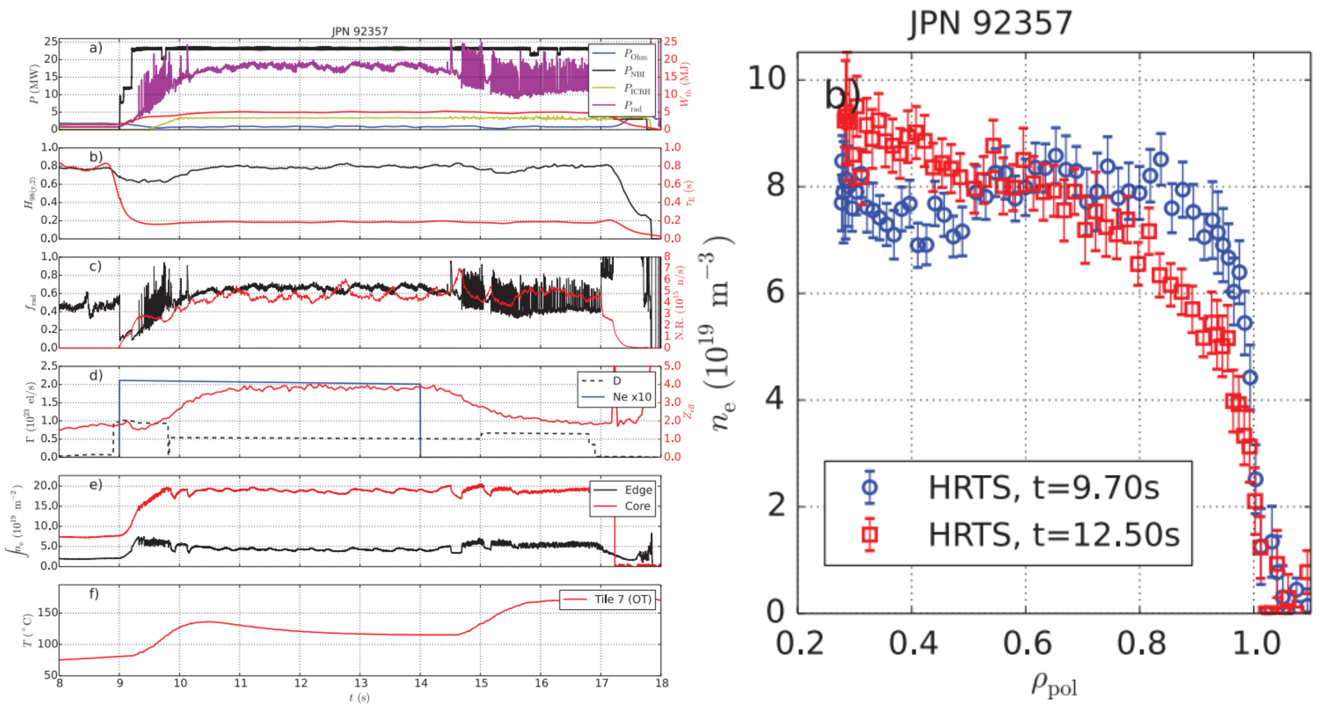
Detached ELM-suppressed regime obtained at AUG and JET for short period with reduction of pedestal density & pressure



ELM suppressed radiating nitrogen seeded regime at AUG,
H_{98} was slightly reduced to less than 1, H_{98}<1

M. Bernert, et al. Nucl. Fusion 61 (2021) 024001



Highly radiating neon seeded plasmas in JET-ILW
A reduction of the pedestal density was observed when neon was seeded.

S. Glöggler, et al. Nucl. Fusion 59 (2019) 126031

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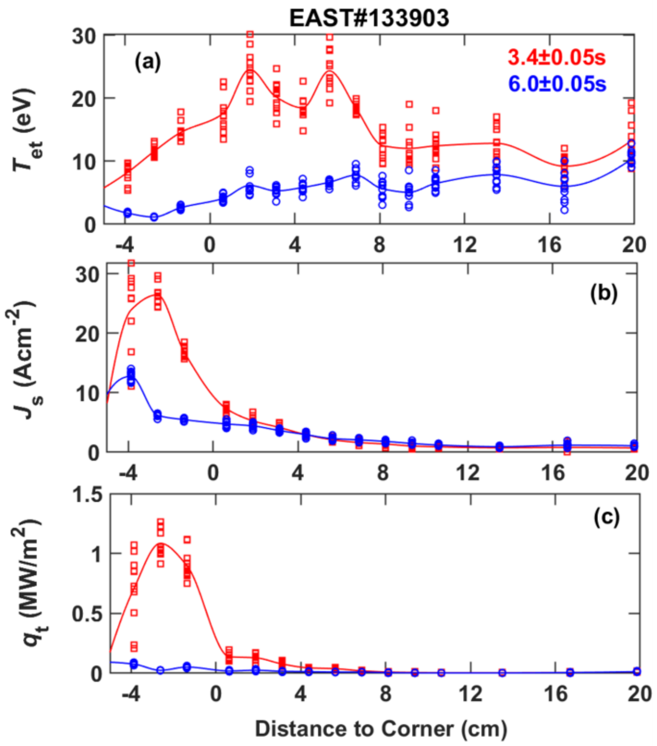
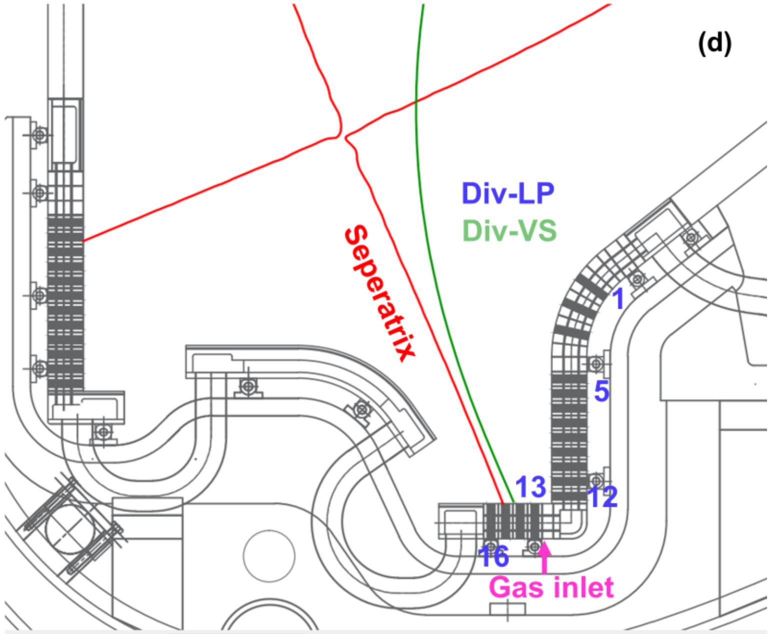
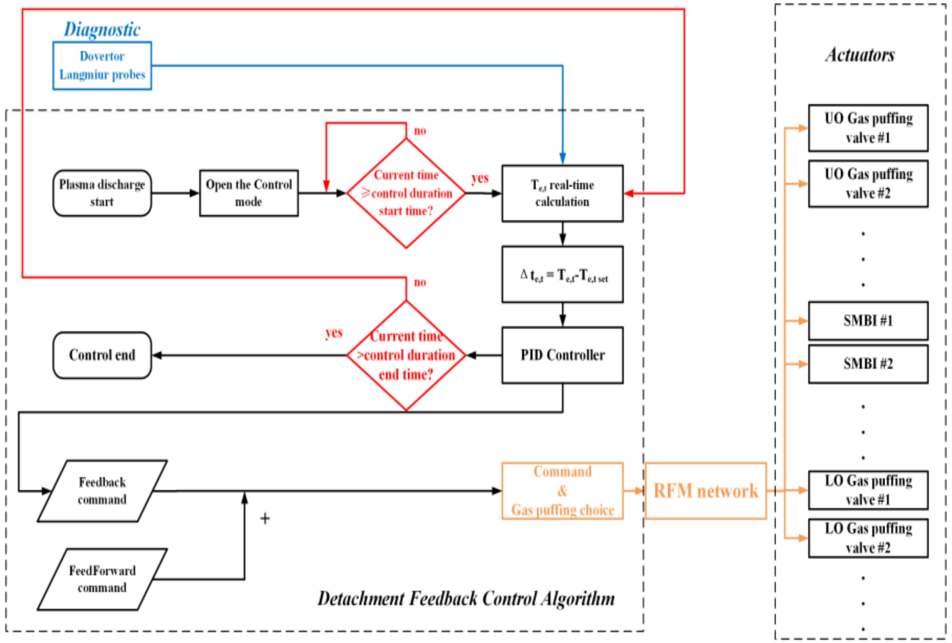
Detachment with feedback control of T_{et} or AXUV radiation near the lower X point via seeding pulse width modulation







Profiles measured by divertor Langmuir probes

Detachment → T_{et} < 5eV

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

Feedback control logic in PSC system

G. S. Xu, et al. Nucl. Fusion 60 (2020) 086001

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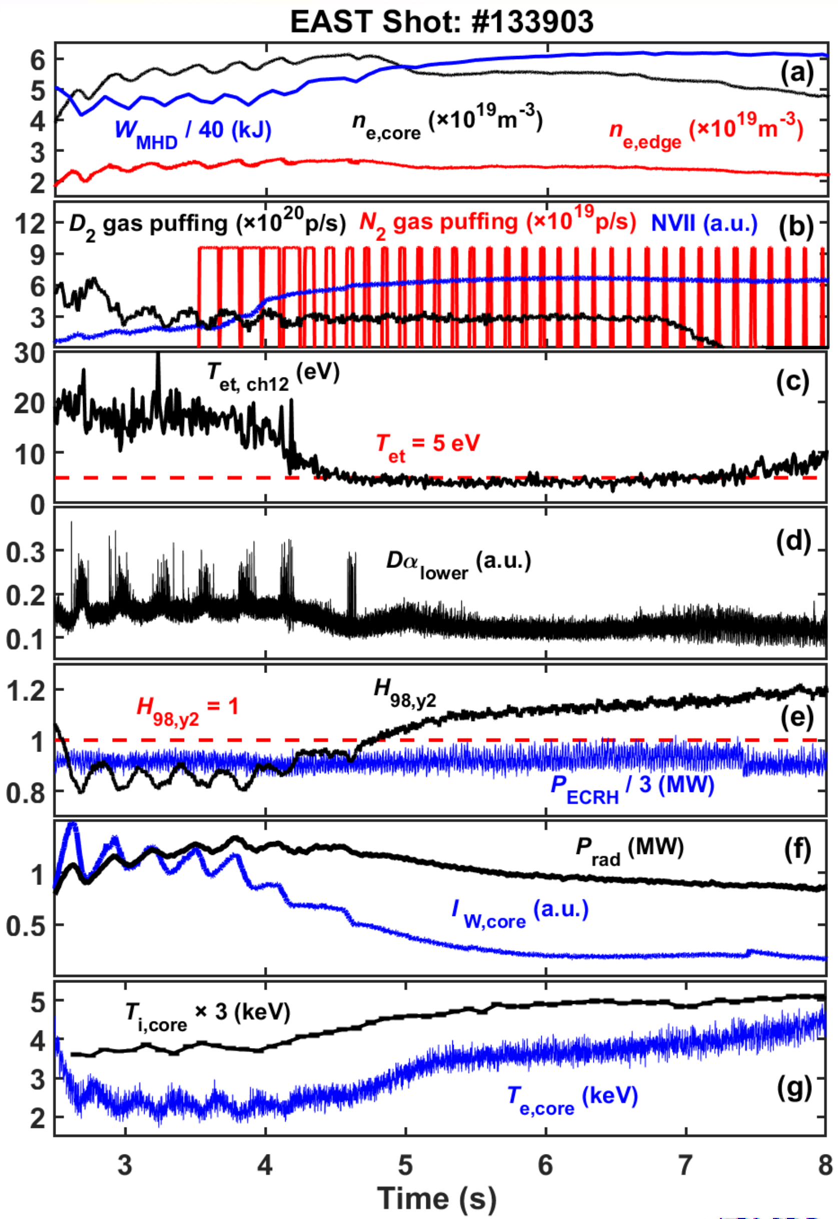
The detached ELM-free H-mode was first obtained at q_{95}=5.2 with H_{98y2} up to 1.2 in short pulses

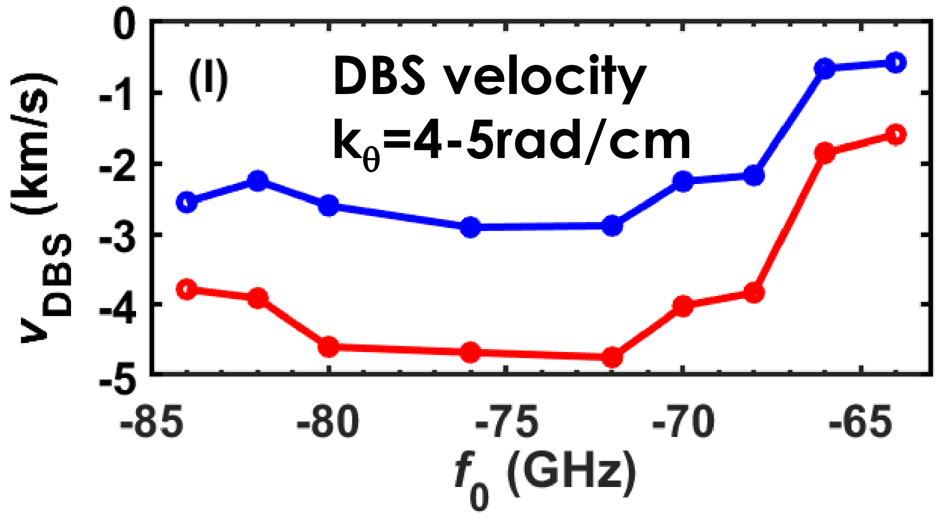
- P_{EC}~2.8MW =1.3-1.8 $P_{L\text{-}H}$
- β_P~1.39, β_N ~1.40, l_i~1.1, q_0~1, κ~1.7, δ_l~0.59, no ITB
- lower-biased double null configuration with dR_{sep}~-4 mm
- Plasma-limiter-surface outer gap dR_{out}~7.3 cm

- **Prior to N_2 seeding, large ELMs appeared intermittently.**
- **ELMs were completely suppressed when detachment was achieved at the lower outer divertor.**
- **H_{98y2} = 0.8-0.9 → 1.1-1.2**
- **W_{MHD}, T_{e0} and T_{i0} increased significantly**
- **n_{el} and n_{eledge} decreased when detachment was achieved**
- **Impurity radiations of tungsten, molybdenum, copper and iron in the plasma core region were significantly reduced**
- **$f_{rad}=P_{rad}/P_{inj}$ decreased continuously from ~50% to ~30%.**
- **These observations suggest that this plasma regime exhibits an excellent particle exhaust and impurity control capability.**

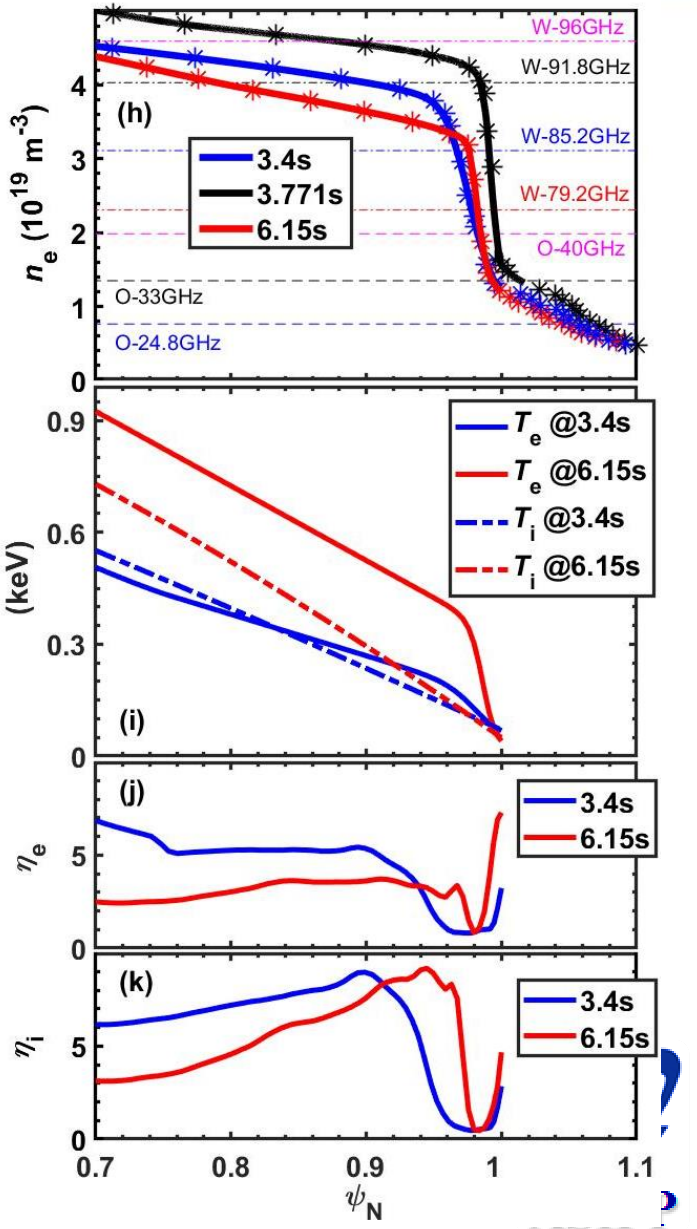


With N_2 seeding, the pedestal n_e and T_e gradients increased

- With N_2 seeding, the pedestal n_e and T_e gradients increased significantly, the density pedestal shifted outward with the density pedestal width being significantly reduced.
- n_e at the top of the pedestal rose at first before divertor detaching and then continued to decrease during divertor detaching, and meanwhile, T_e at the top of the pedestal nearly doubled.
- η_e and η_i are small in the pedestal steep density gradient region, but large at the pedestal top due to low density gradient there.

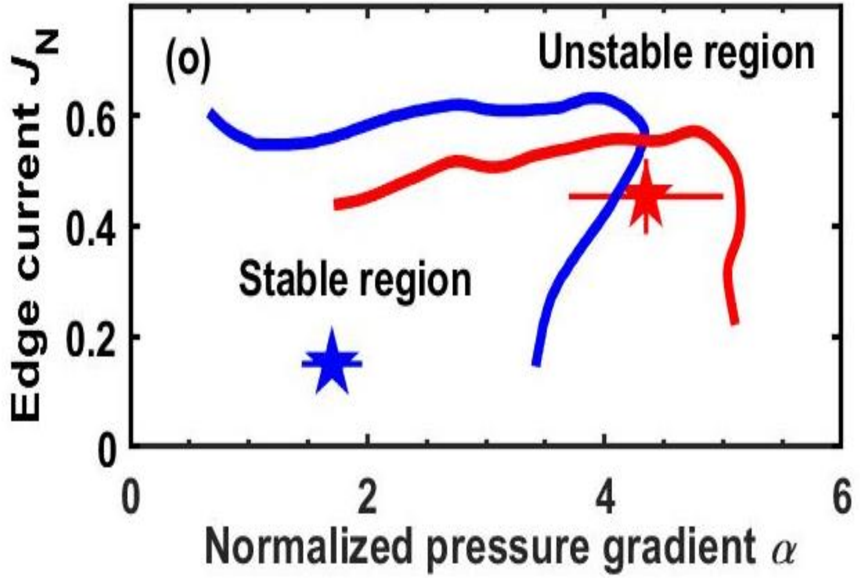


Velocity in the pedestal region measured by DBS becomes much more negative in the electron diamagnetic direction, which may be responsible for the enhanced energy confinement.

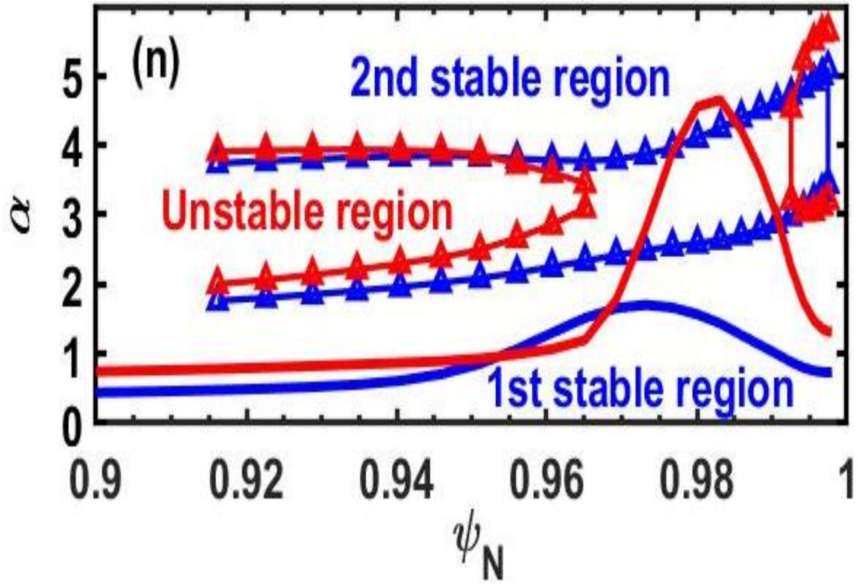


Pedestal MHD stability analysis

- **Linear stability analysis of the pedestal ideal PB modes using ELITE code.**
  - Prior to N_2 seeding, the pedestal is in the PB mode deeply stable region. However, the intermittent bursts of ELM clusters were observed during the experiment, which may be associated with resistive non-ideal MHD effects, such as resistive ballooning modes.
  - During N_2 seeding, the pedestal is in the stable region, but close to the corner between the peeling boundary and the ballooning boundary.



- **Stability boundaries of infinite-*n* ideal ballooning modes analyzed with BALOO code**
  - Prior to N_2 seeding, the pedestal is in the first stable region of ideal ballooning modes.
  - During N_2 seeding, the pedestal enters the second stable region of ballooning modes, which may explain why the ideal ballooning modes remains stable.



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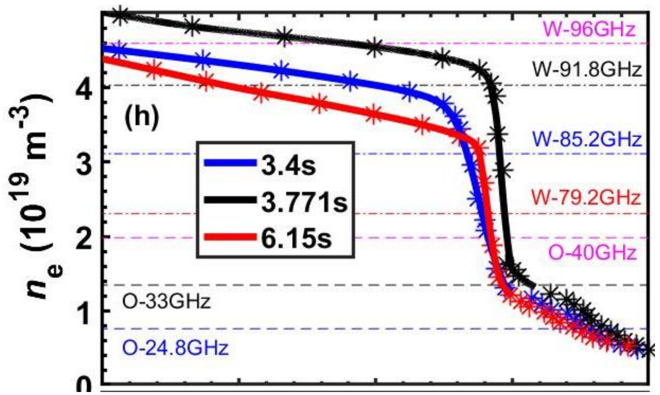
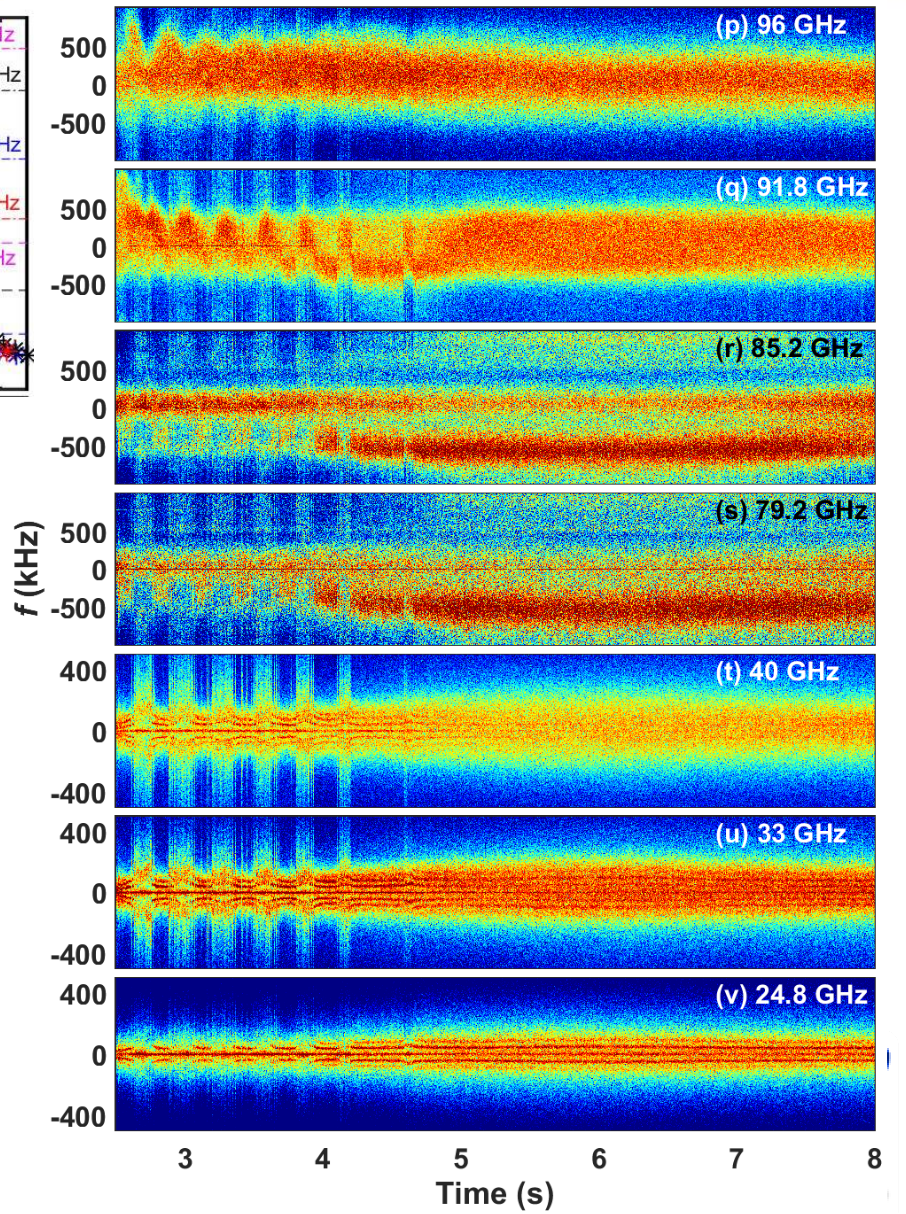
Turbulence frequency spectra measured by a multichannel poloidal correlation reflectometer in the pedestal region

- During N_2 seeding, a high-frequency turbulence with a peak frequency at ~600 kHz, propagating in the electron diamagnetic direction, appears in the steep-density-gradient region.



- It was not visible to the high-frequency Mirnov magnetic coils, suggesting that it could be an electrostatic mode.
- At the pedestal top, where η_i is large due to low density gradient, a broad-band turbulence peaking at low frequency appears both before and during N_2 seeding.
- In the lower region of the pedestal and in the SOL, a mode at a frequency of ~40 kHz with multiple harmonics is present in the ELM-free phases, which is ECM, usually seen in the H-mode pedestal region of EAST at high collisionality, which was identified as DTEM.

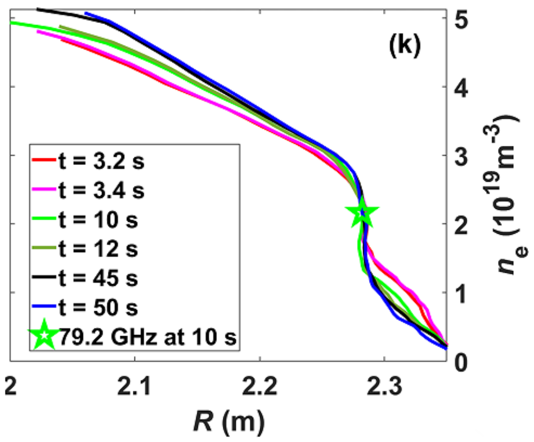


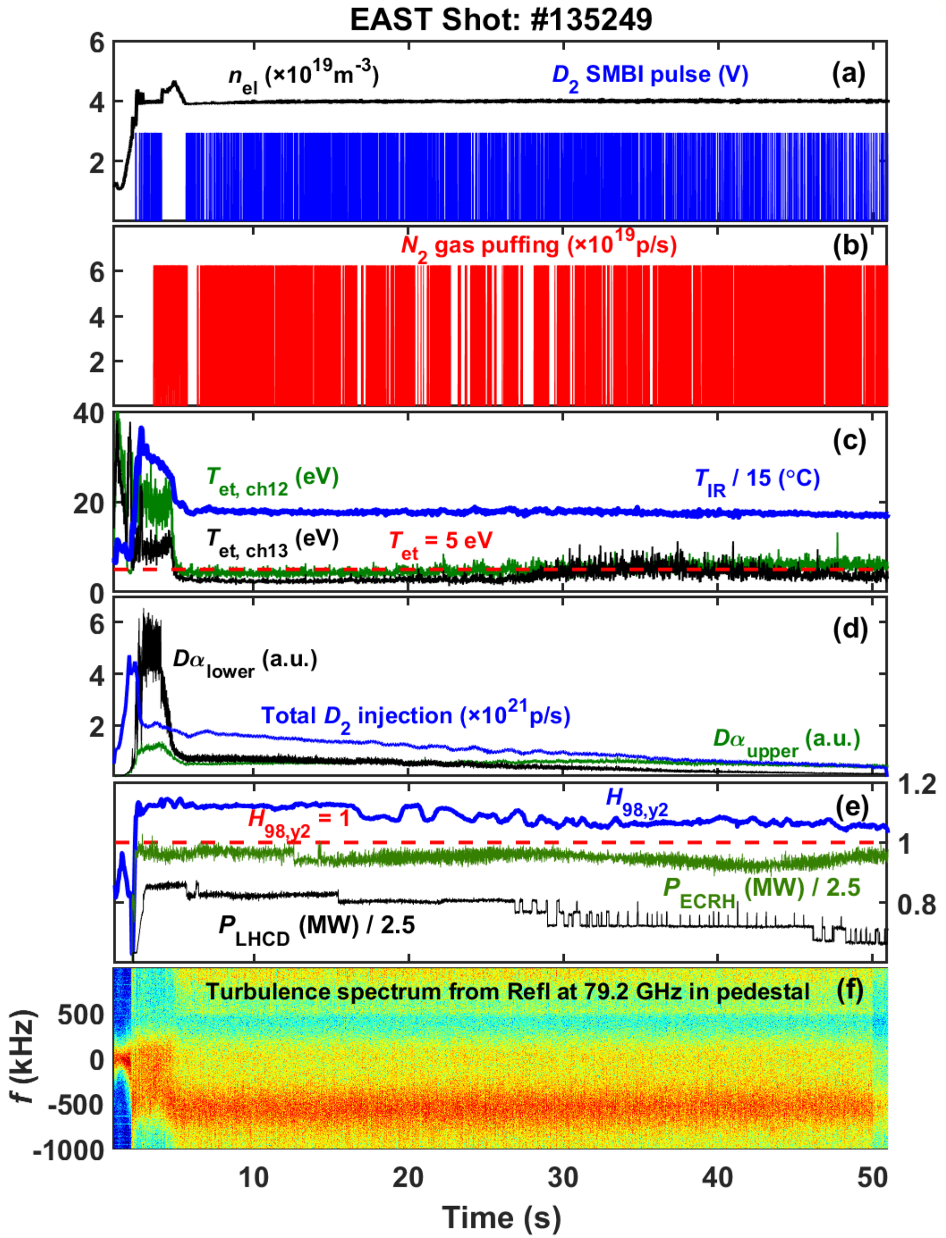
50s long-pulse stationary detached ELM-free H-mode plasma at q_{95}=6.2 with H_{98y2} up to 1.1 (reduce Ip = 500 → 400 kA)

– P_{EC}~2.5MW + P_{LHCD}~1.9MW = 2.2 $P_{L\text{-}H}$
– β_P~1.55, β_N ~1.36, 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%

- **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°C to ~250°C.**

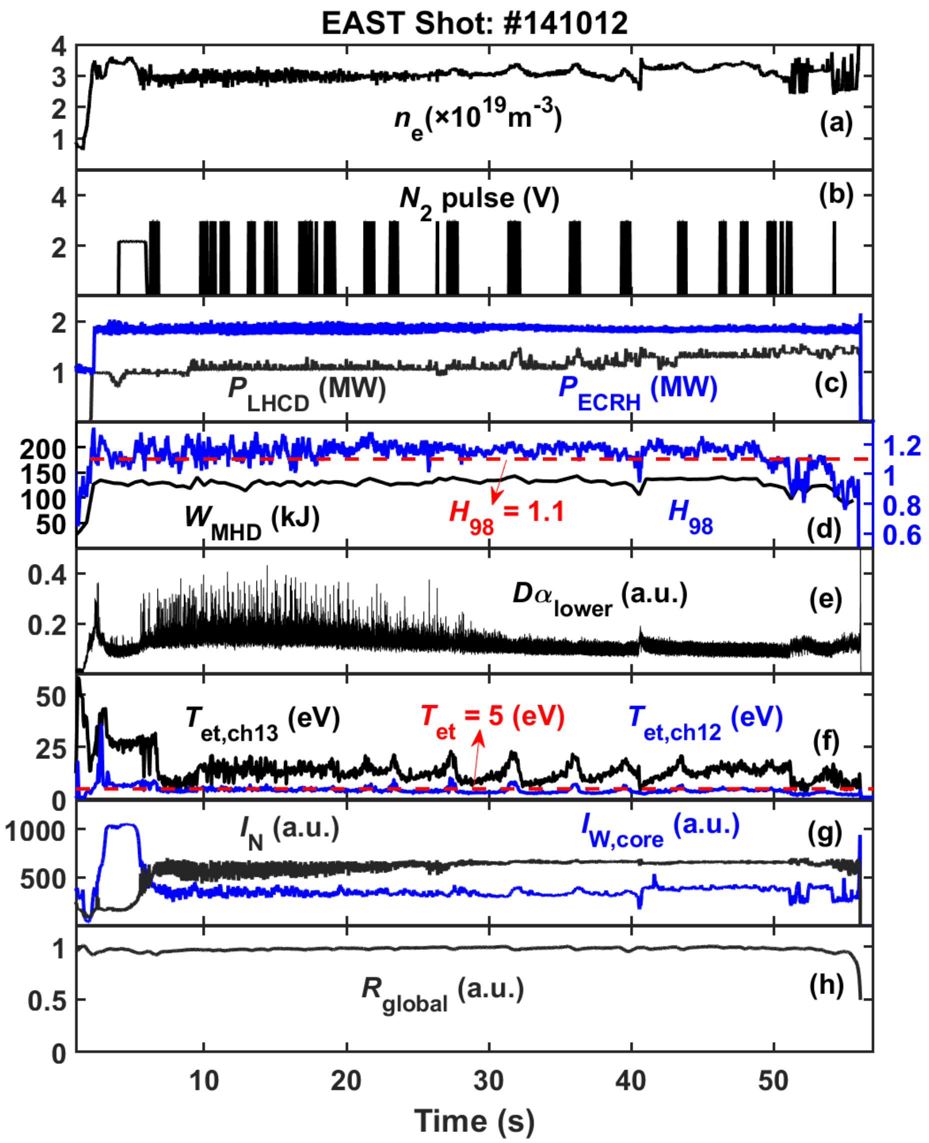
- **Divertor Dα drops sharply when N_2 seeding begins and then continues to decrease. At the same time, the total D_2 injection rate also continues to decrease and n_e in the SOL significantly decreases, suggesting a reduction in the particle recycling from the walls and an increase in the pedestal density gradient.**

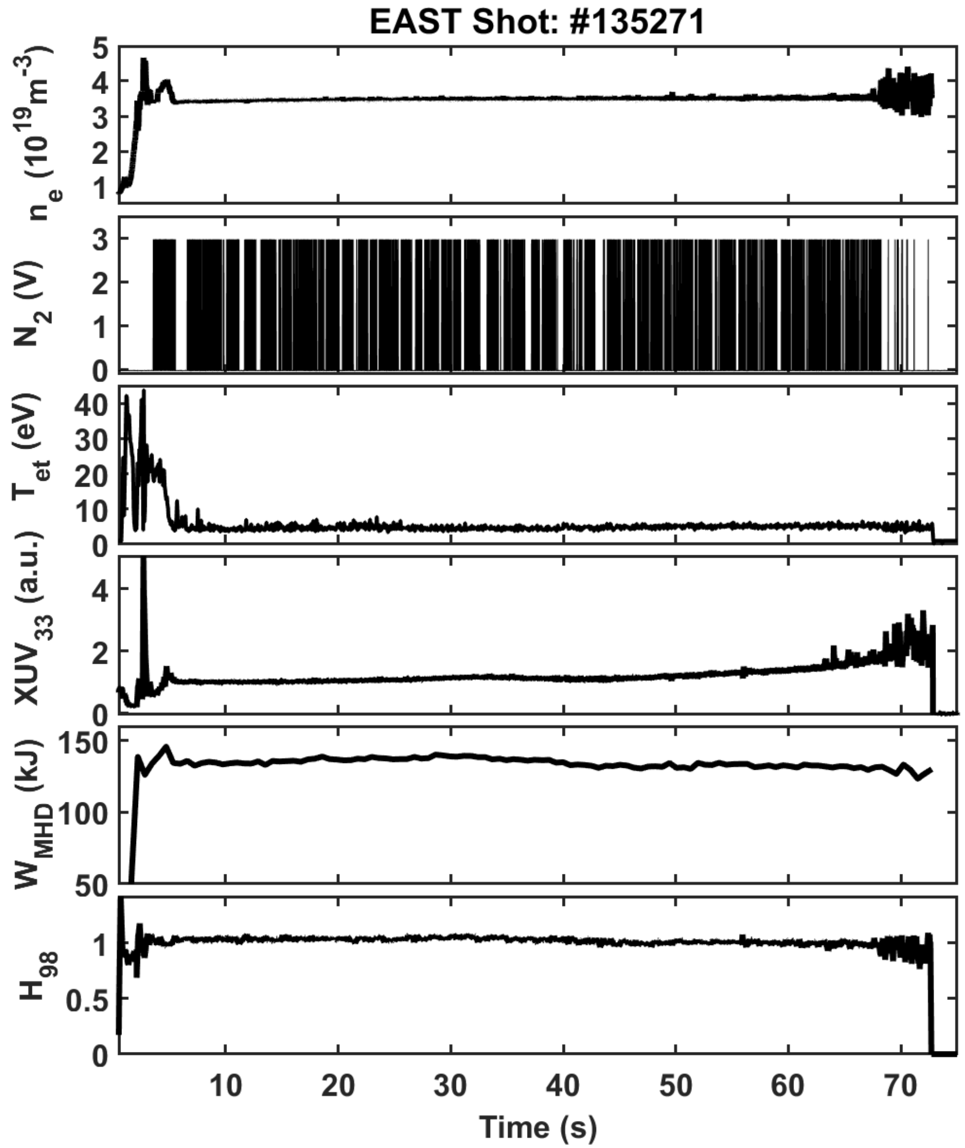




- **The high-frequency turbulence appears.**

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





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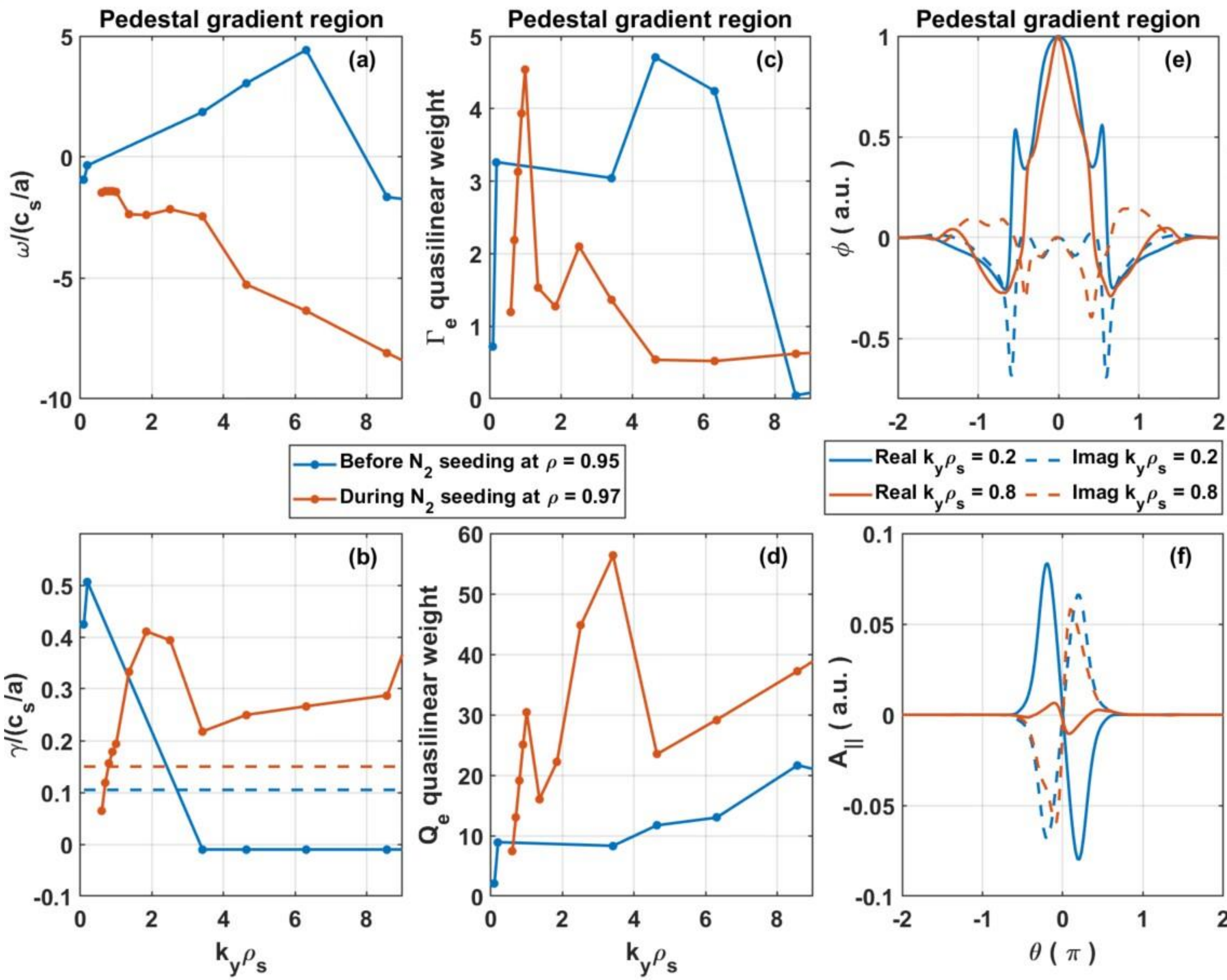
ε_n-TEM ($k_y\rho_s$=0.6-3.4) in the pedestal gradient region drives outward particle and electron heat fluxes during N_2 seeding

- **Before N_2 seeding, the simulations show a low-frequency ε_n-TEM in the low $k_y\rho_s$=0.1-0.2 range, consistent with the characteristics of the low-frequency turbulence seen in the experiments.**

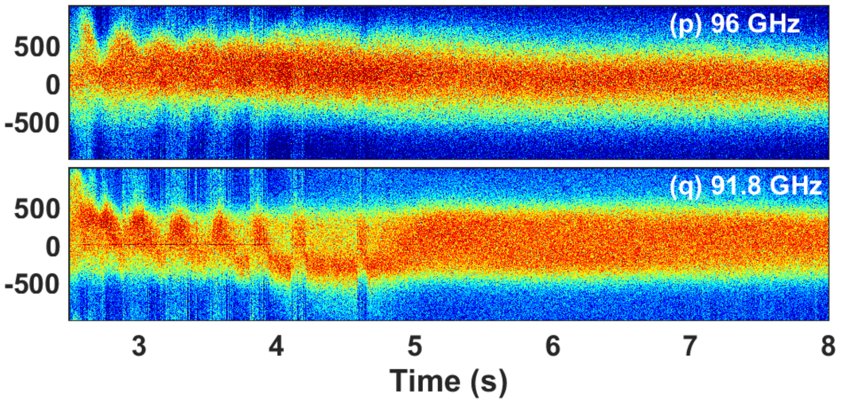
- **During N_2 seeding, the simulations show ε_n-TEM ($k_y\rho_s$=0.6-3.4) with the linear growth rate exceeding the local ExB shear rate, which is destabilized by both density and temperature gradients, in good agreement with the most features of the experimentally observed high-frequency turbulence.**

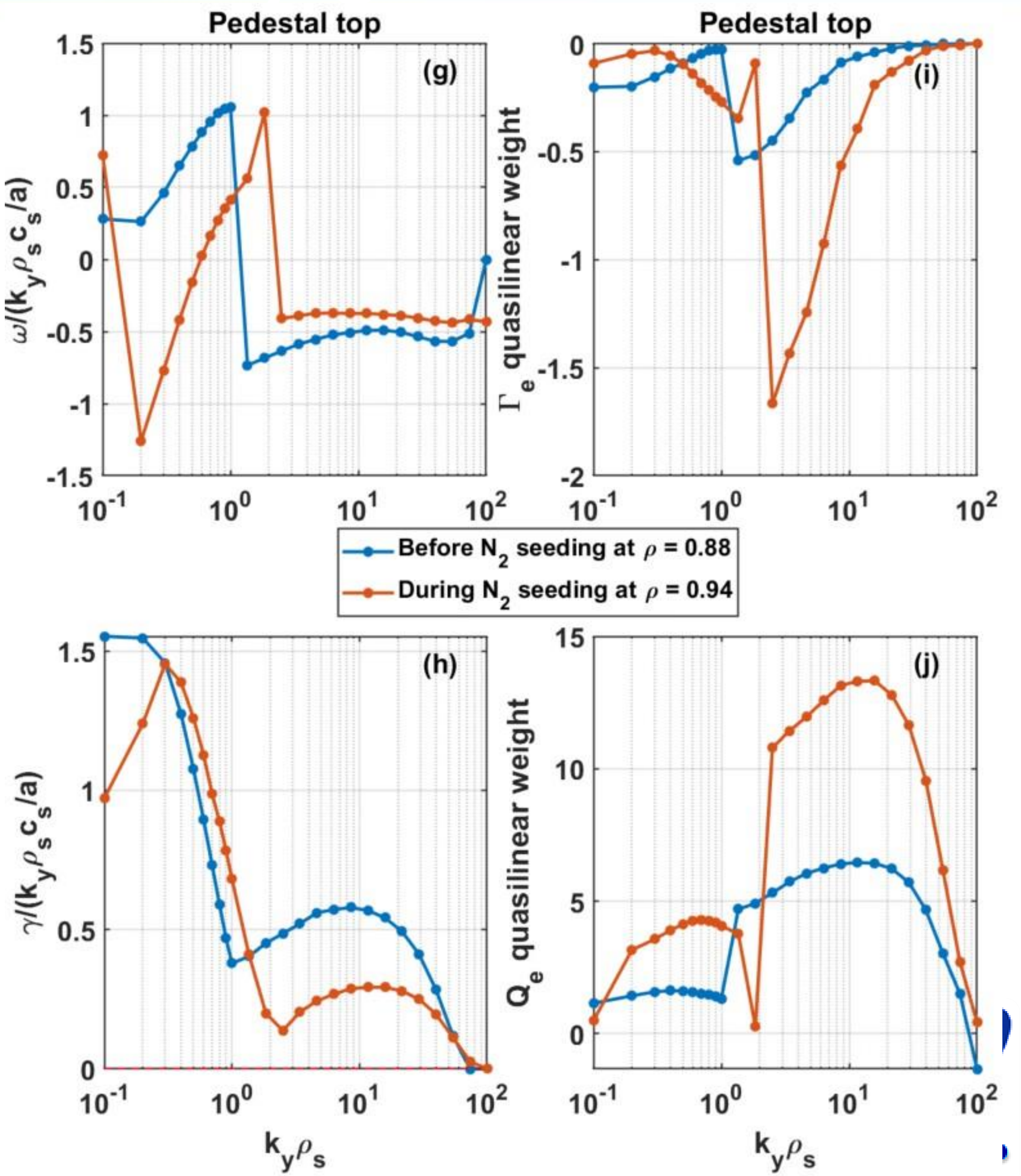
- **This mode drives radially outward particle and electron heat fluxes, providing a radial transport channel across the pedestal, which may be responsible for the ELM suppression.**



Coupled ITG-TEM and ETG modes appear at the pedestal top where η_i and η_e are high due to low density gradient

- Before N_2 seeding, the simulations show ITG in the low $k_y\rho_s$=0.1-1.0 range and ETG in the high $k_y\rho_s \geq 1.0$ range at the pedestal top where η_i and η_e are large due to low density gradient.
- During N_2 seeding, the simulations show coupled ITG and TEM in the low $k_y\rho_s$=0.1-1.2 range, and ETG in the high $k_y\rho_s \geq 1.3$ range.
- The ITG is consistent with the experimentally observed low-frequency turbulence quite well.
- Both the ITG and ETG modes drive inward particle flux and outward heat flux.





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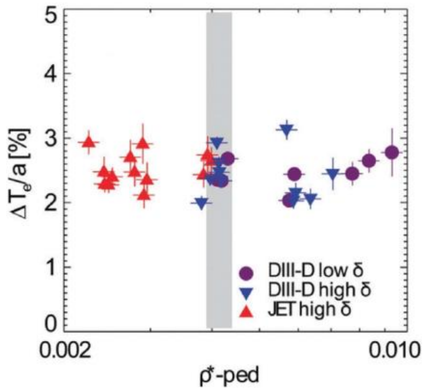
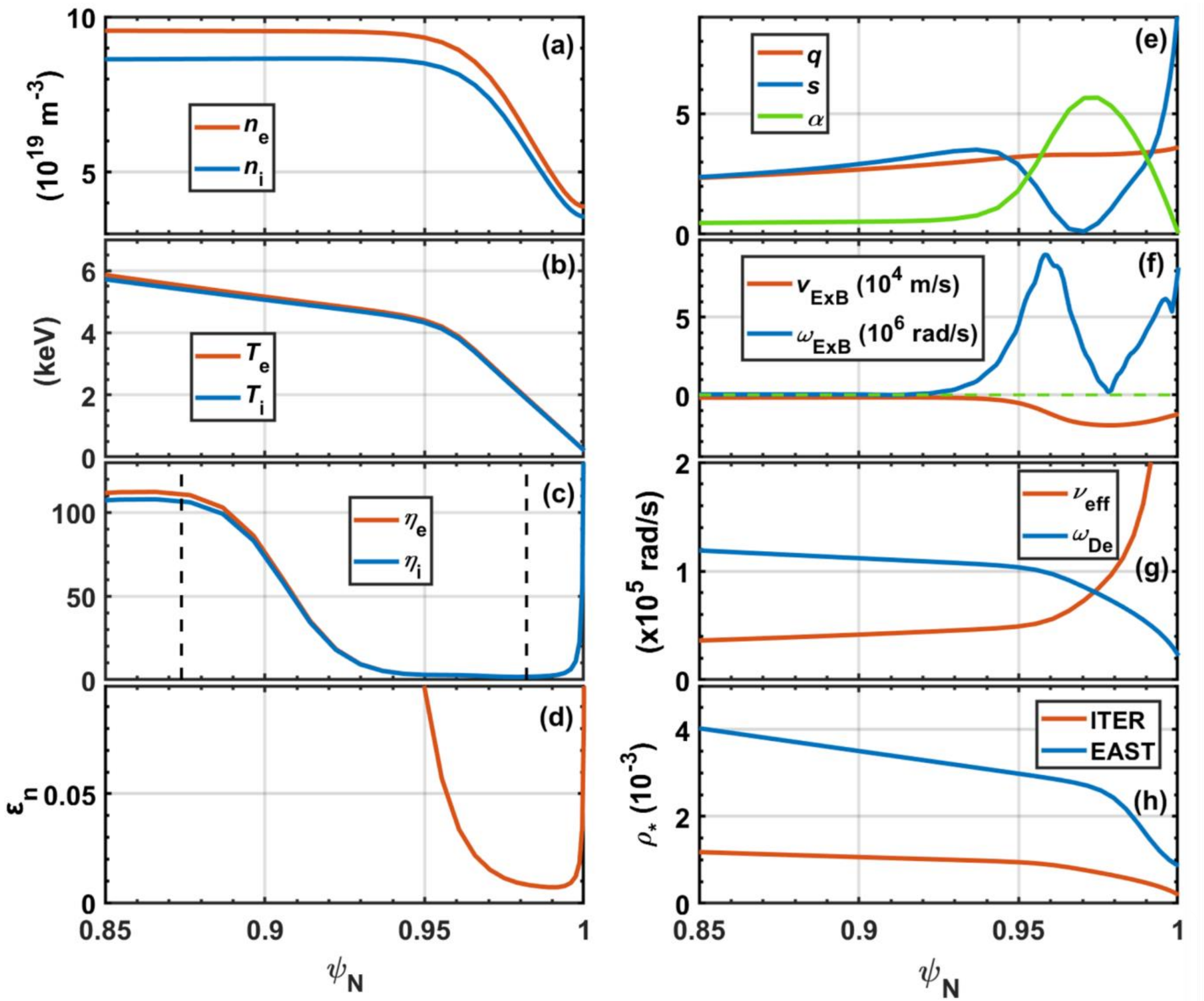
ITER Ip=15MA baseline scenario generated by CORSICA integrated modeling code with the pedestal based on EPED

- **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.**



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η_e-TEM and ITG appear in the pedestal gradient region, ITG and ETG appear at the pedestal top of ITER baseline scenario

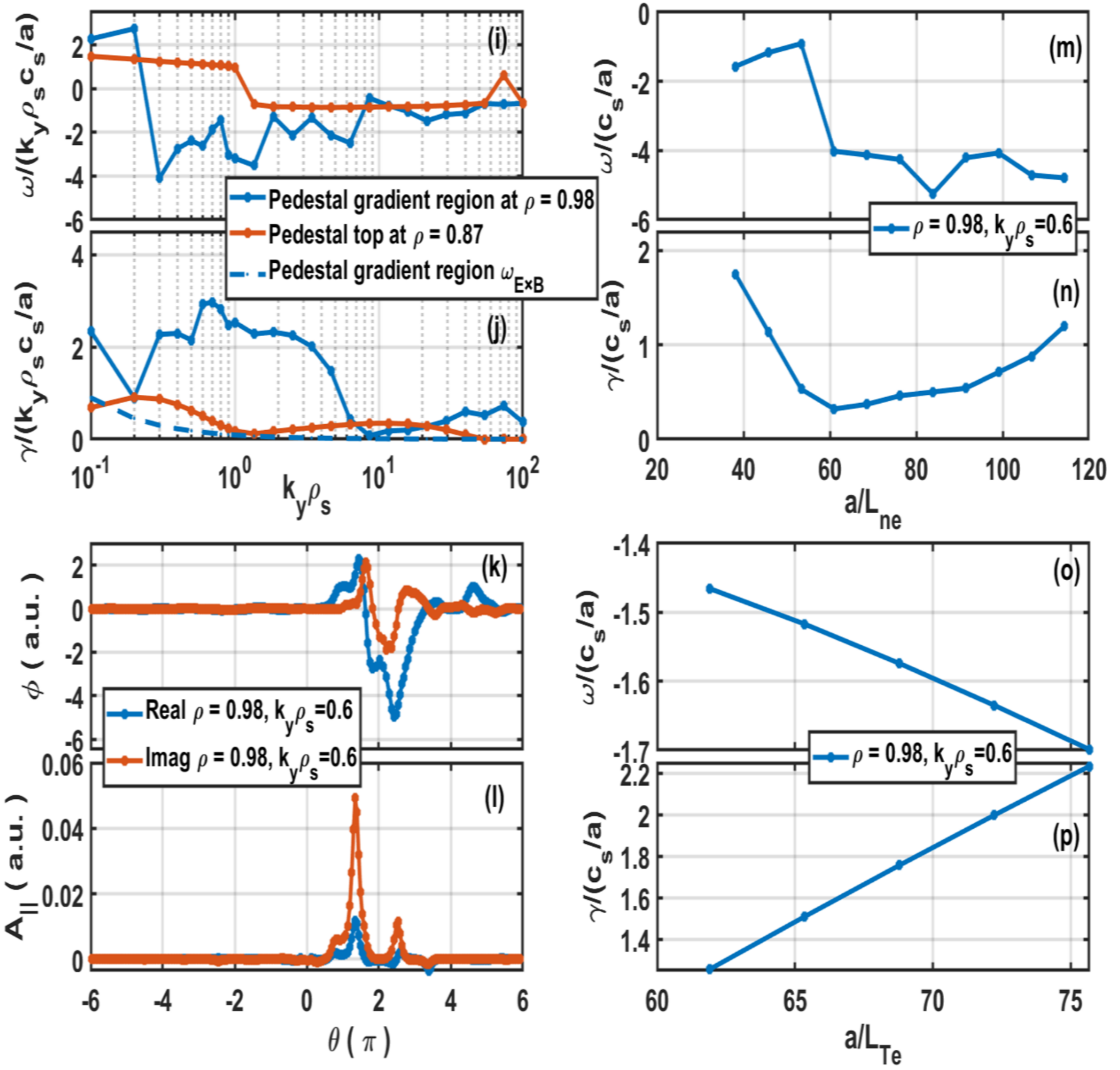
- **The simulations show η_e-TEM and ITG in the pedestal gradient region with their linear growth rates well above the local ExB shear rate.**

- **The η_e-TEM, which has not been seen in the high-collisionality pedestal of EAST, appears in the pedestal region of ITER due to the low collisionality.**

- **At higher density gradients, the η_e-TEM transitions to the ε_n-TEM in ITER, similar to that in EAST.**

- **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. However, our simulations predict that the pedestal region of the ITER baseline scenario may be naturally ELM-free, due to the presence of strong turbulent transport.**



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Long-pulse no-ELM H-mode operation with feedback-controlled detachment under boronized metal wall in EAST

- Under metal-wall conditions, it is particularly important to provide an exhaust channel for impurities across the pedestal and suppress large ELMs to avoid accumulation of metallic impurities in the plasma core, which can degrade the energy confinement.

- The newly demonstrated long-pulse high-performance H-mode regime in EAST, where pedestal turbulence replaces ELMs with feedback-controlled divertor detachment under ITER-like conditions, i.e., boronized full-metal wall and high-power ECRH heating, provide a promising solution to achieve long-pulse stable operations under full-metal-wall conditions.

- H-mode with impurity-seeded divertor detachment is expected to be the routine operational scenario for ITER. If spontaneous ELM suppression can be achieved at the same time, it would be a desirable scenario. Then, there is in principle no need to use external control tools or specialized schemes, such as RMPs or negative triangularity, for ELM suppression, which add to the complexity and cost of fusion reactors.

- Stronger turbulences, which are more likely to appear in the ITER pedestal region than in present tokamaks, may render large ELMs to disappear naturally, and thus the current widespread concerns about ELM control reliability and core metal impurity accumulation may not pose a major obstacle for ITER to achieve its scientific goal.

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Current issues

1. Currently longer pulses can only be obtained by lowering I_p. To achieve long pulses at lower q_{95} for this regime, increased current drive is required.

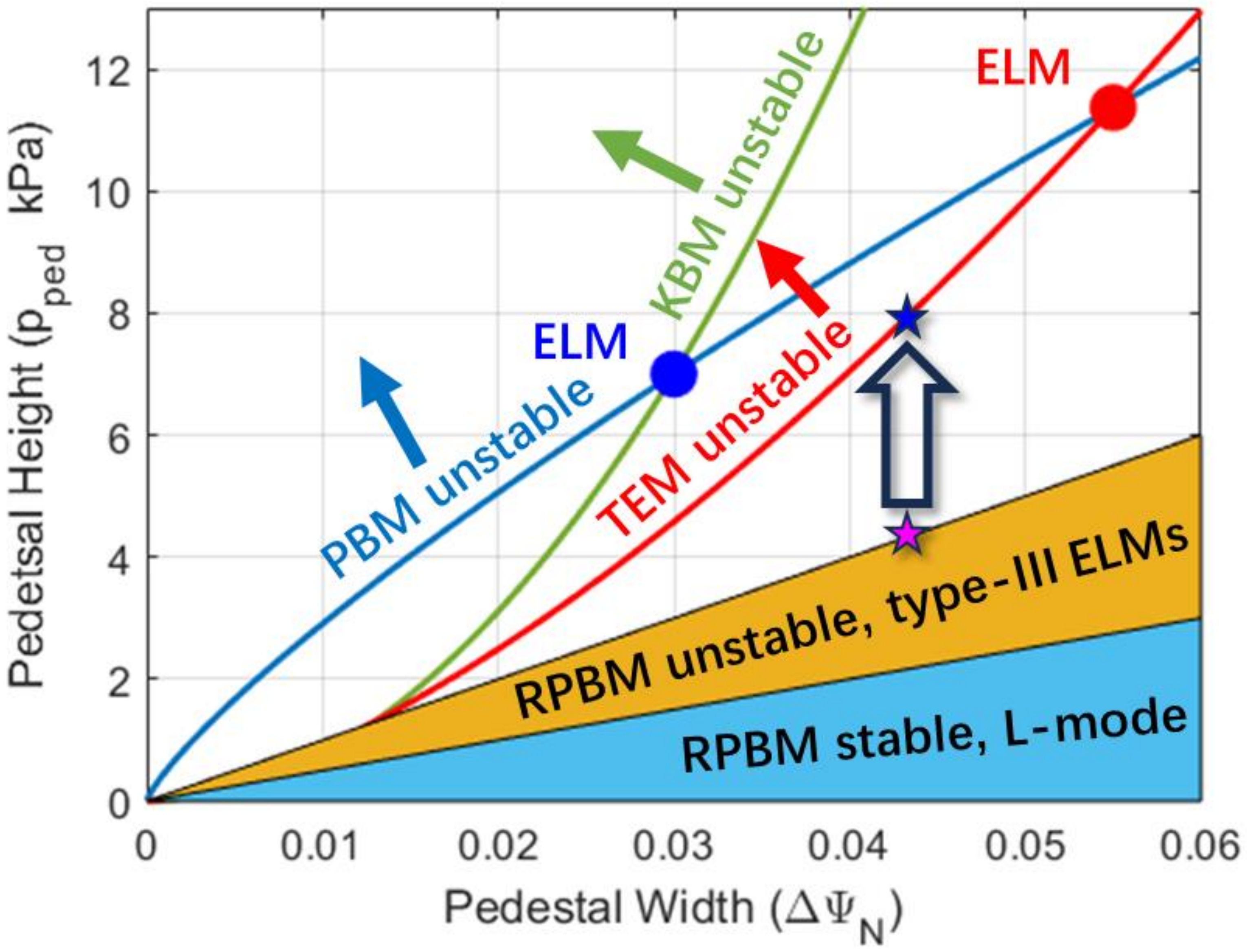
2. Although the divertor detachment suppresses the metal impurity source from the divertor, the outer gap is small for good LHCD coupling. The injected low-Z impurities enhance the impurity sputtering of the limiters and antennas on the low-field side. Long-distance coupling with increased outer gap is needed to solve this problem.

3. Nitrogen retention on the wall is large and affects the next discharge. Need at least one cleaning discharge. Hot wall operation will be needed in the future to solve this problem.

Thank You

Schematic diagram of physical principle of ELM suppression caused by pedestal turbulence based on the EPED model

- **When the pedestal temperature is relatively high and the collisionality is relatively low, the EPED model assumes that type-I ELMs occur at the intersection point of the PBM and KBM instability boundaries.**
- **When the density gradient in the steep gradient region of the pedestal increases, it excites ε_n-TEM turbulence and limits the pedestal gradient so that it cannot touch the KBM instability boundary.**
- **Since the intersection point of the PBM and TEM instability boundaries is at a very high pedestal height and a very wide width, when the heating power is not sufficient, the PBM instability boundary will not be touched, so there is no ELM.**



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