First Edge-Localized Mode Suppression With Lower Hybrid Waves on the EAST Tokamak

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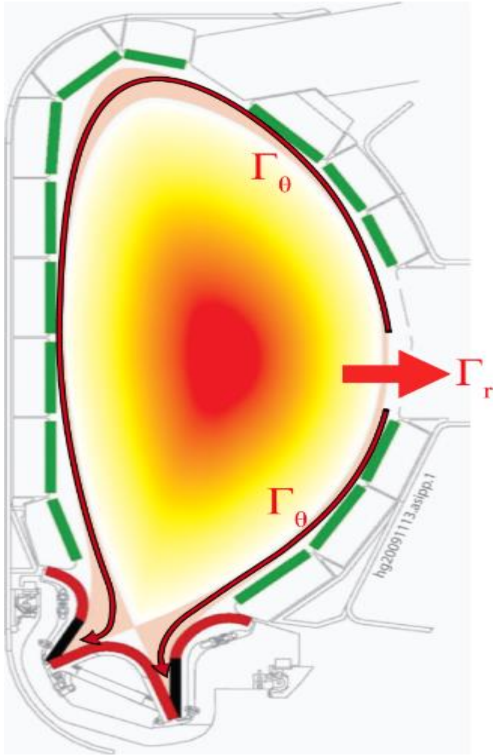
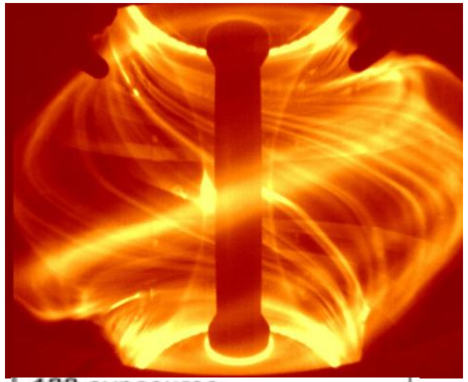
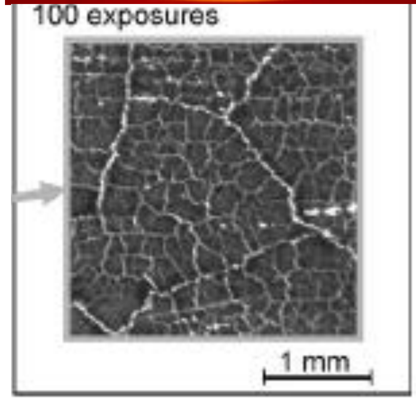
Outline

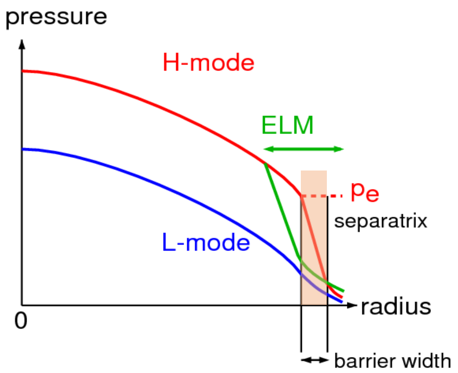
- Background
- Development of Directional Electron Probe
- Measurement and model of helical current filaments (HCFs) induced by LHWs
- ELM suppression with LHWs on EAST
- Summary

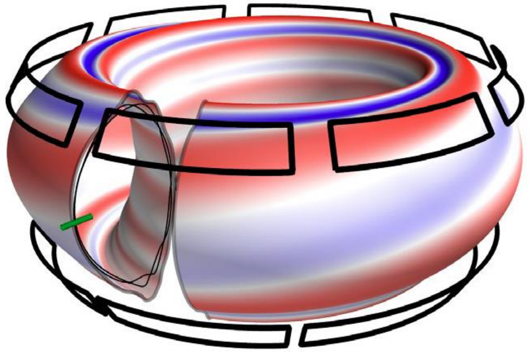
Edge-Localized Mode (ELM)



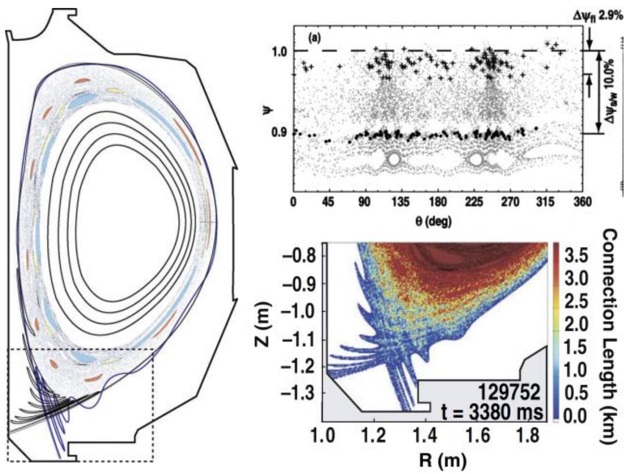


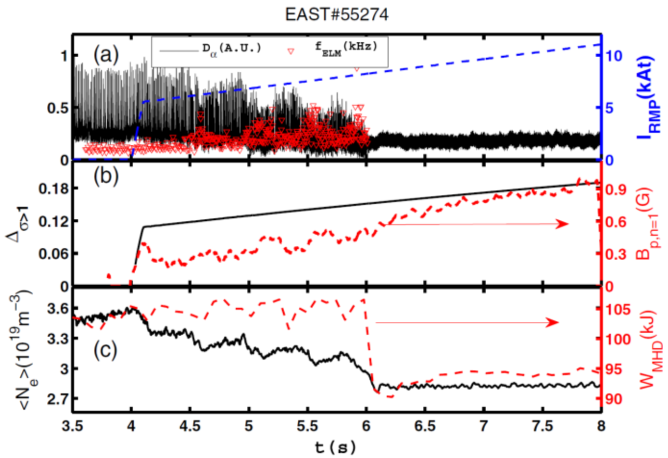






- A fraction of the plasma energy is transferred to the open field lines during ELM eruption, result in high transient heat load in divertor targets.
- Resonant magnetic perturbation (RMP) is an effective method to control ELM.





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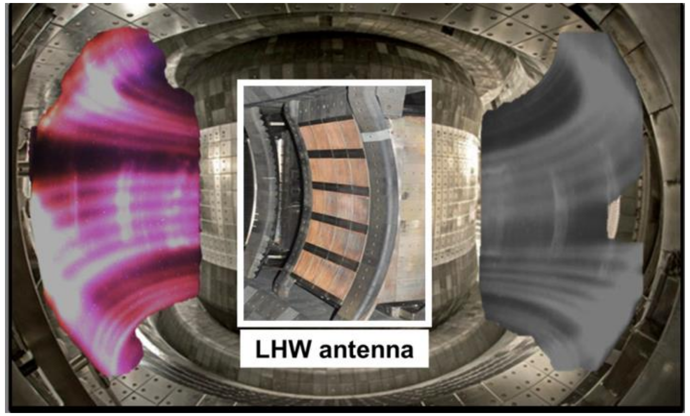
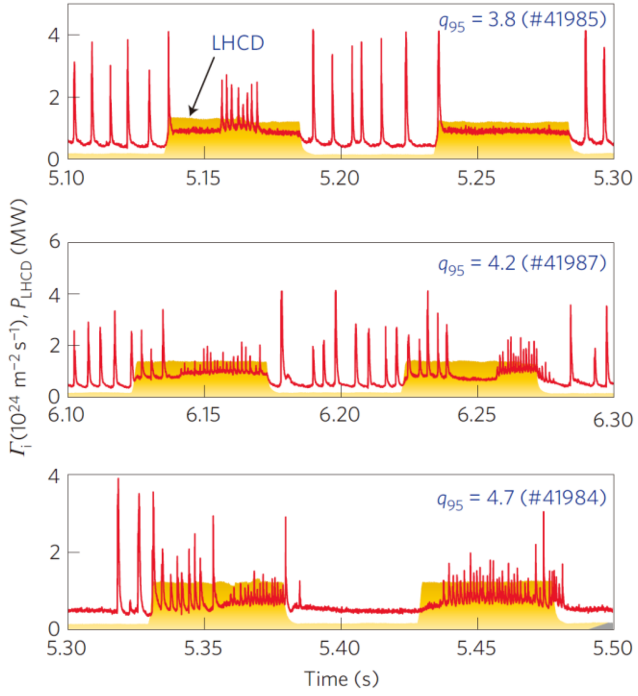
ELM Control with Lower Hybrid Wave





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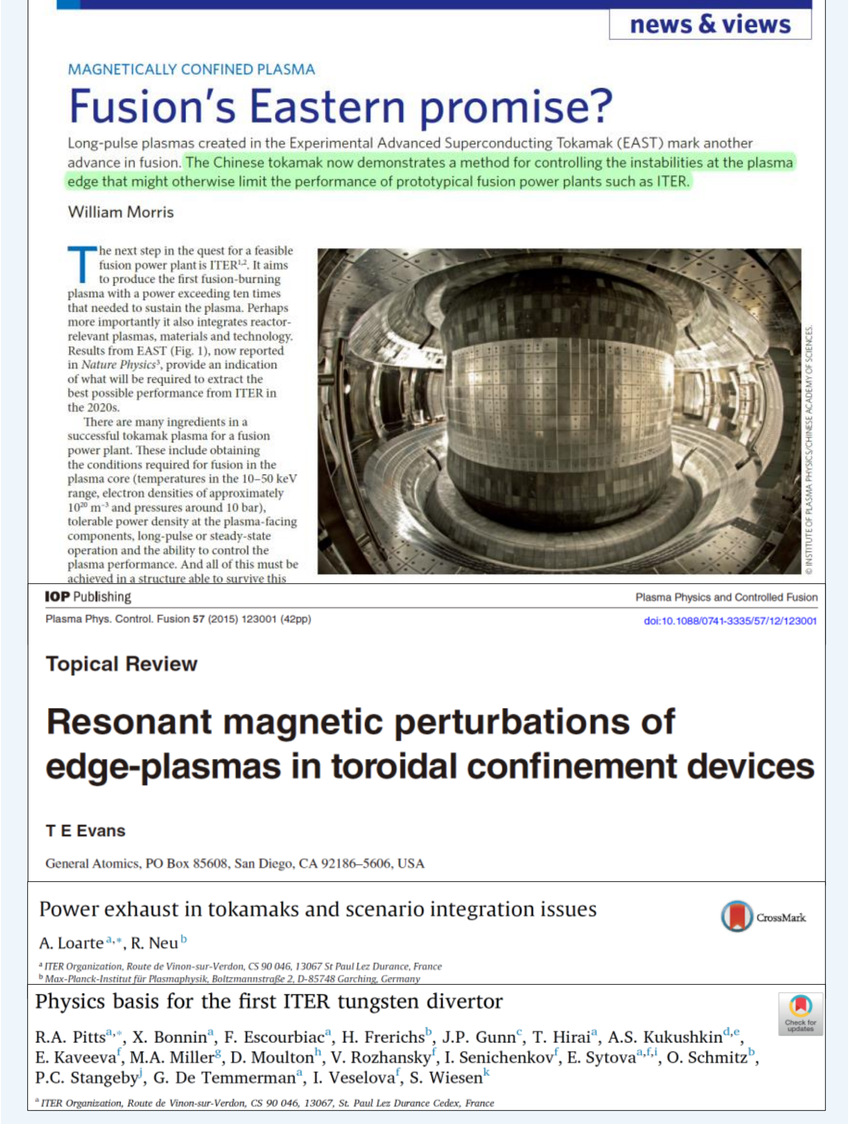
[2] Y. Liang *et al* 2013 Phys. Rev. Lett. 110 235002



news & views

MAGNETICALLY CONFINED PLASMA

Fusion's Eastern promise?

Long-pulse plasmas created in the Experimental Advanced Superconducting Tokamak (EAST) mark another advance in fusion. The Chinese tokamak now demonstrates a method for controlling the instabilities at the plasma edge that might otherwise limit the performance of prototypical fusion power plants such as ITER.

William Morris

The next step in the quest for a feasible fusion power plant is ITER[1,2]. It aims to produce the first fusion-burning plasma with a power exceeding ten times that needed to sustain the plasma. Perhaps more importantly it also integrates reactor-relevant plasmas, materials and technology. Results from EAST (Fig. 1), now reported in *Nature Physics*[3], provide an indication of what will be required to extract the best possible performance from ITER in the 2020s.

There are many ingredients in a successful tokamak plasma for a fusion power plant. These include obtaining the conditions required for fusion in the plasma core (temperatures in the 10–50 keV range, electron densities of approximately 10^{20} m^{-3} and pressures around 10 bar), tolerable power density at the plasma-facing components, long-pulse or steady-state operation and the ability to control the plasma performance. And all of this must be achieved in a structure able to survive this

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Topical Review

Resonant magnetic perturbations of edge-plasmas in toroidal confinement devices

T E Evans

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Power exhaust in tokamaks and scenario integration issues

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Physics basis for the first ITER tungsten divertor

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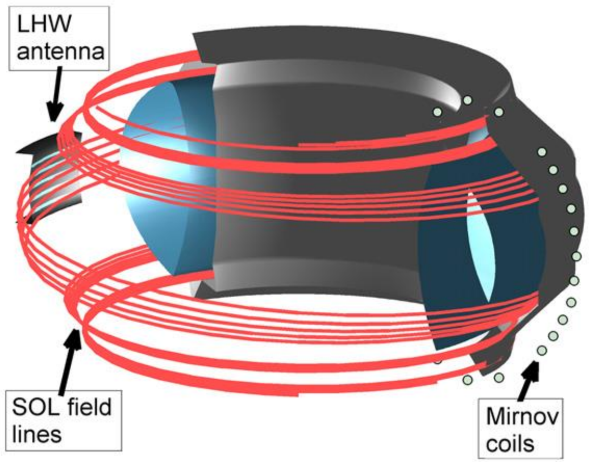
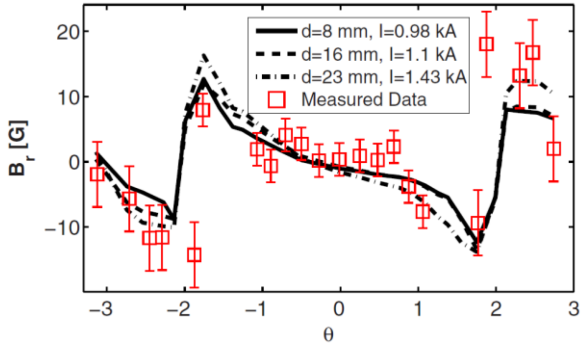
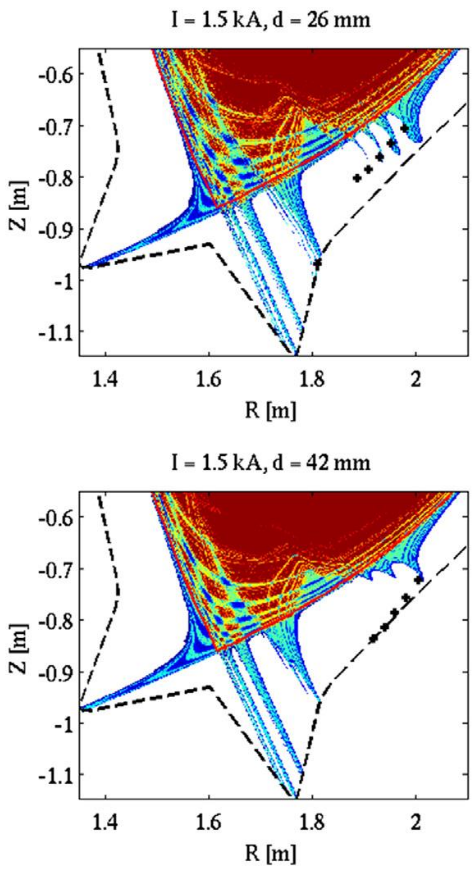
[a] *ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067, St. Paul Lez Durance Cedex, France*

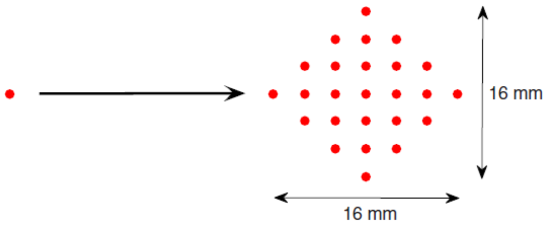
- LHWs drive SOL current filaments, generate edge RMPs, control ELM and divertor heat load.
- ELM mitigation was achieved by LHW modulation on EAST in 2012.

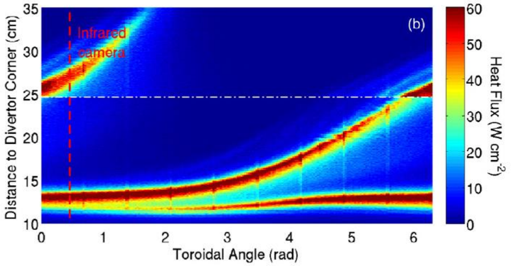
Modelling of ELM Control with LHWs

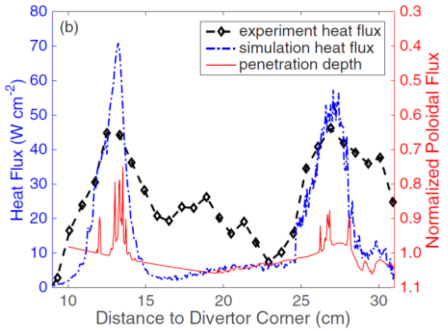


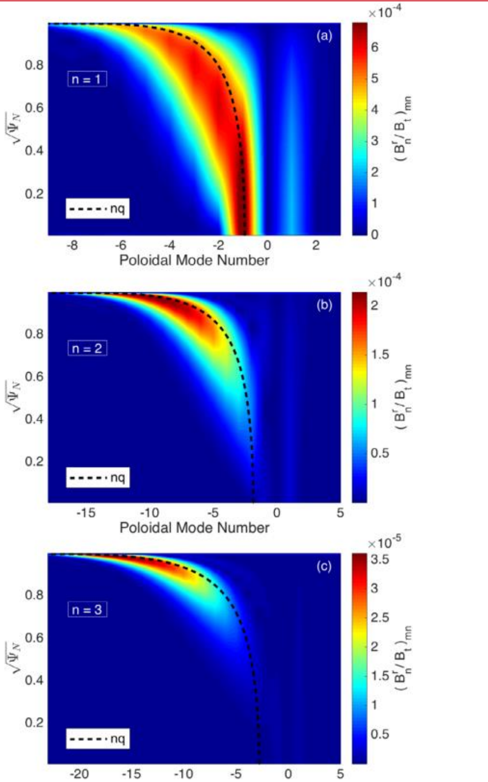












Rack M. *et al* 2014 Nucl. Fusion 54 064016
Xu S. *et al* 2018 Nucl. Fusion 58 106008

- Modelling of HCFs induced by LHWs is built by field line tracing, and simulate the magnetic topology effects.
- It is essential to measure the SOL current profiles induced by LHWs and develop an accurate model.

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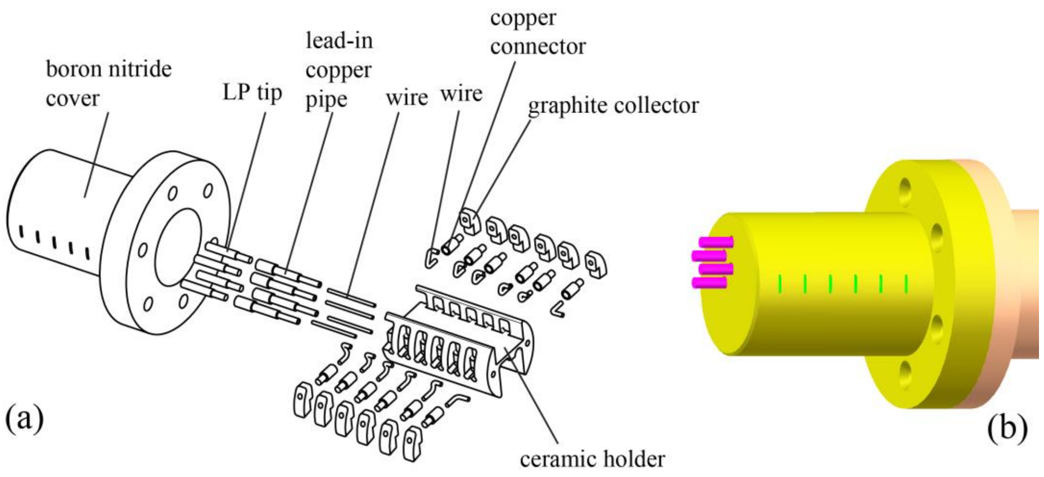
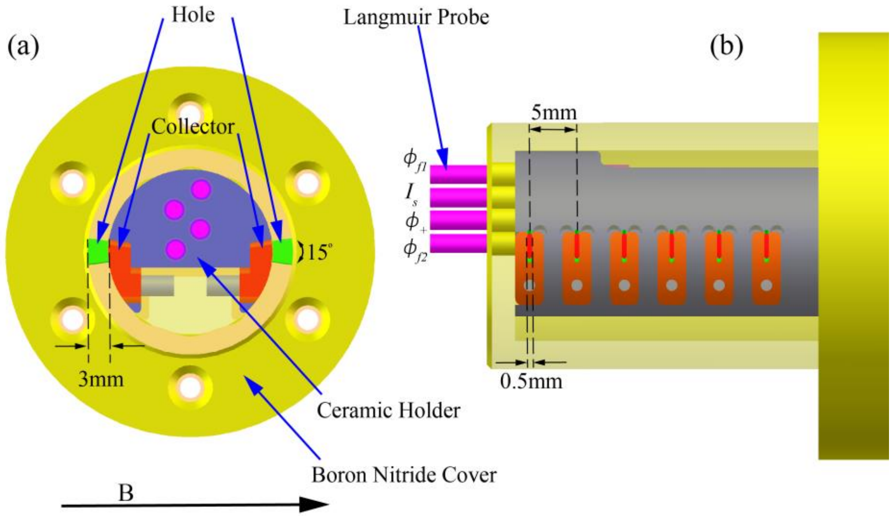
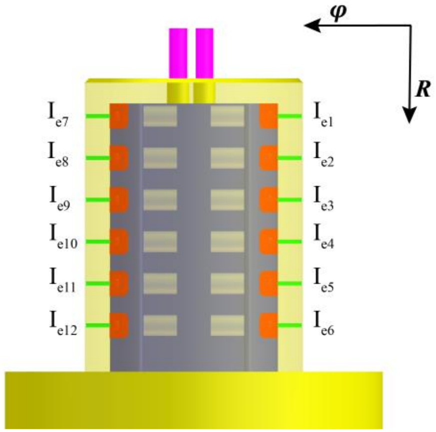
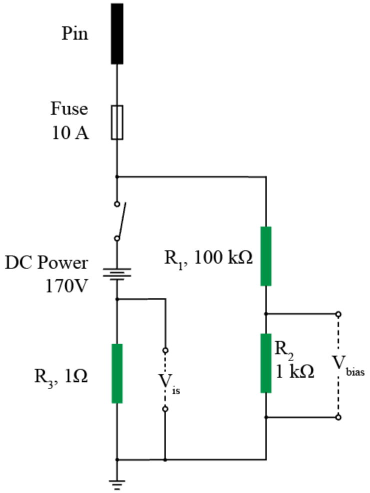
Directional Electron Probe (DEP)



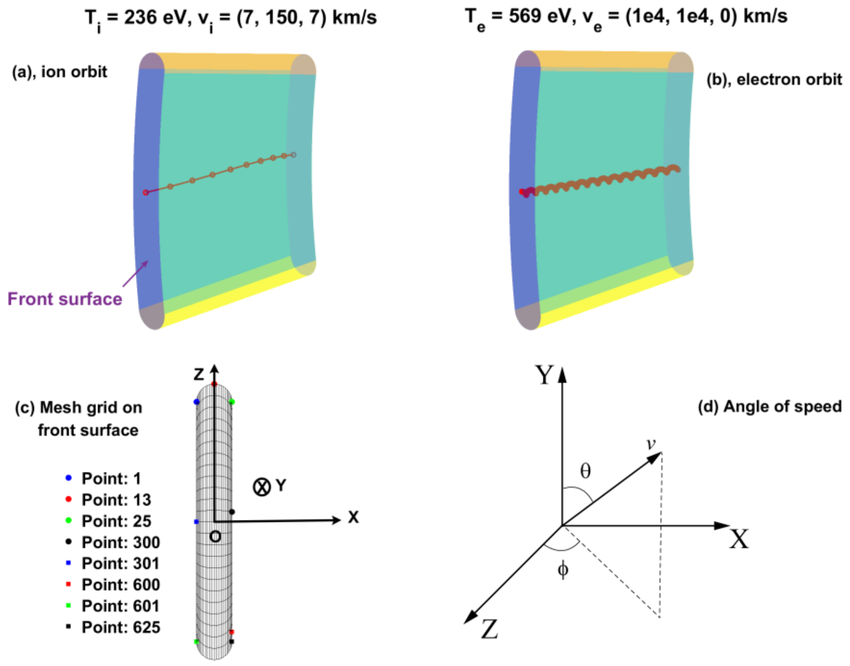


- DEP is developed to measure SOL non-thermal electron current.
- Principle： $\rho_i \gg \rho_e$, collector is embedded inside a pinhole and biased to positive voltage ⟶ collects electrons and repel ions ⟶ non-thermal electron current from the difference of the opposite sides
- Pinhole: width 0.5 mm, depth 3 mm; separated by 5 mm radially

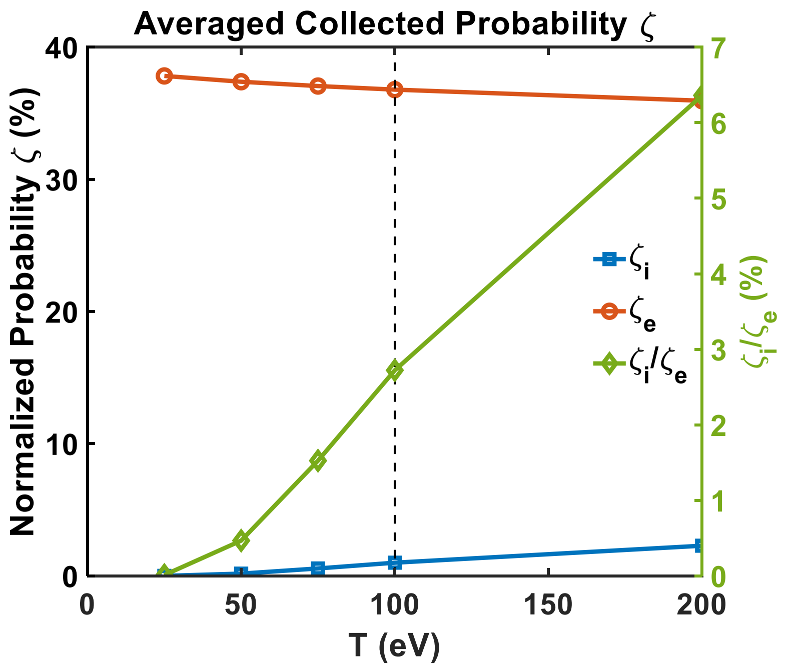




Verification of DEP Principle by Particle Orbit Simulation



S. C. Liu *et al* 2021 Nucl. Fusion 61 126004



Averaged Particle Collection Probability

- Particle orbit simulation is performed to validate the principle of DEP.
- Electrons have much higher collection probability than ions.

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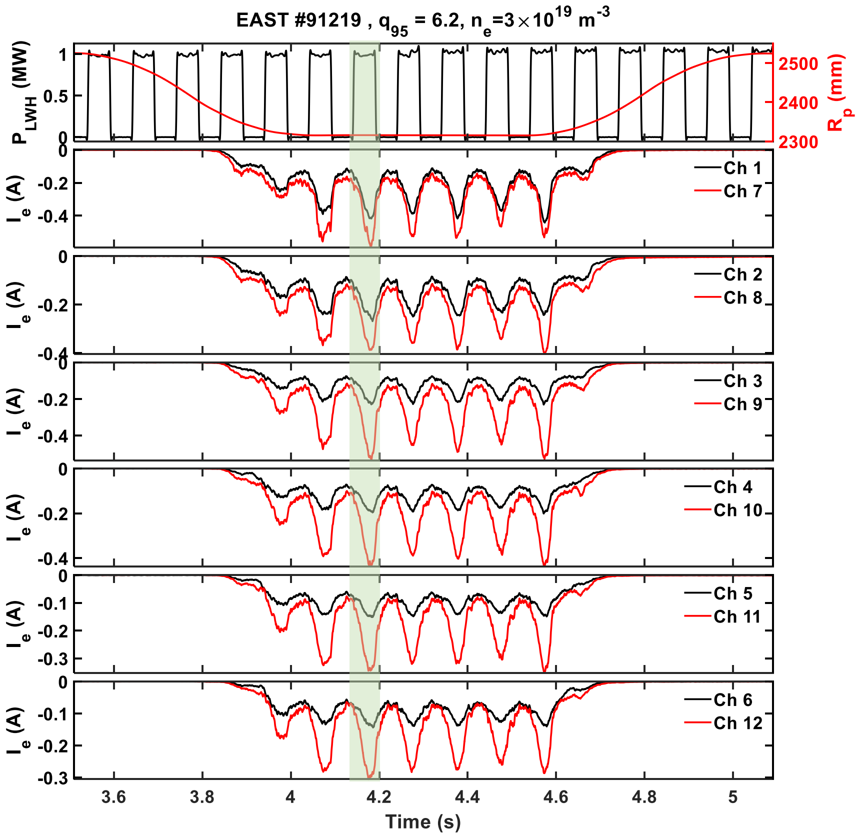
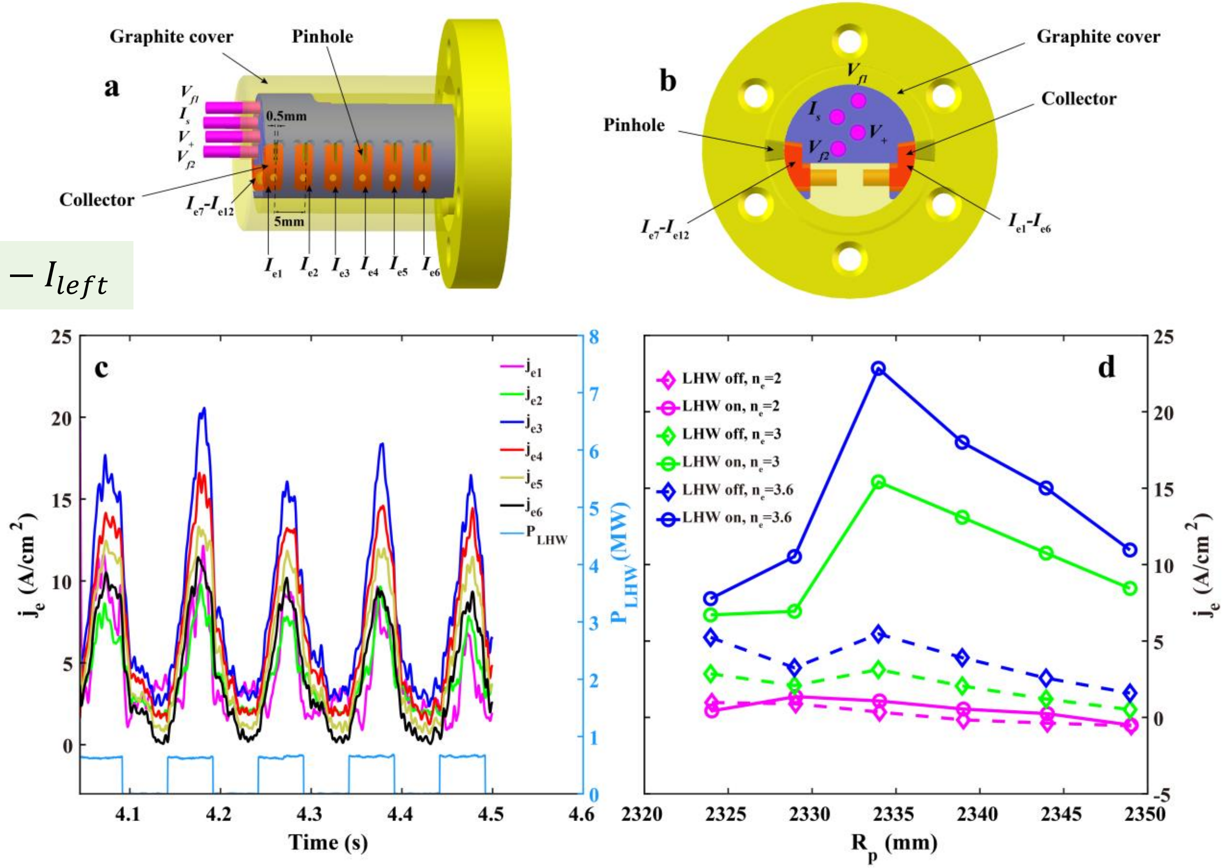
Direct Measurement of helical current filaments (HCFs) in SOL

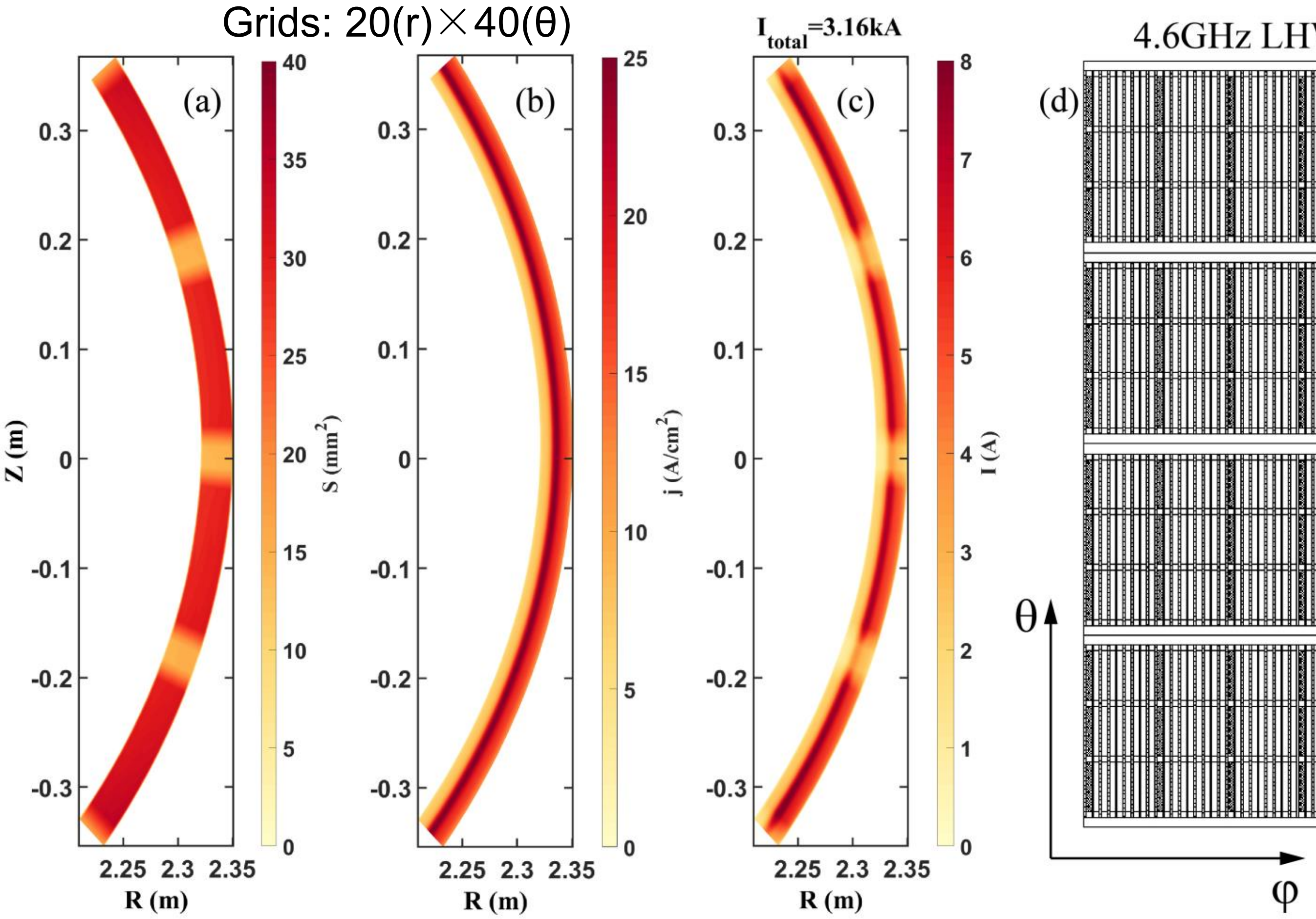


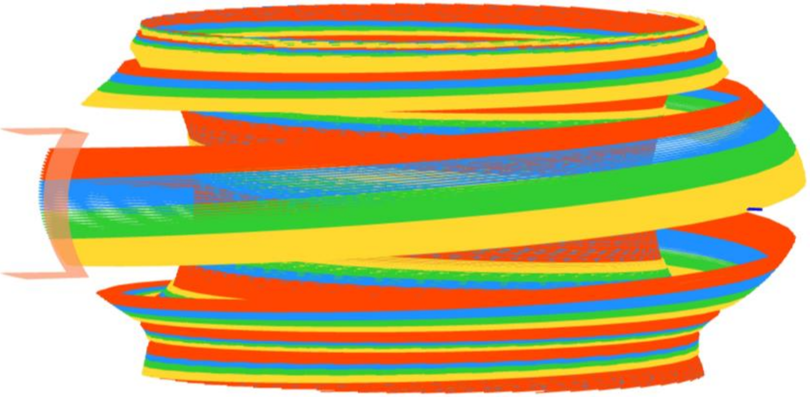
$$I_{net} = I_{right} - I_{left}$$

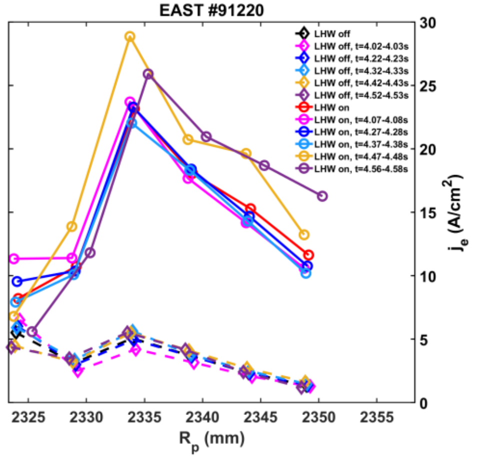


- ➢ LHW is modulated at 10 Hz with a 50% duty cycle.
- ➢ HCF peaks at $R \approx 2335$ mm, covers a wide radial region (>20 mm), with a maximum 20 A/cm^2.
- ➢ Clear density threshold ($n_{e,threshold} \approx 2.8 \times 10^{19}$ m^{-3}) is observed for the SOL HCFs.

Modelling of HCFs According to Direct Measurement

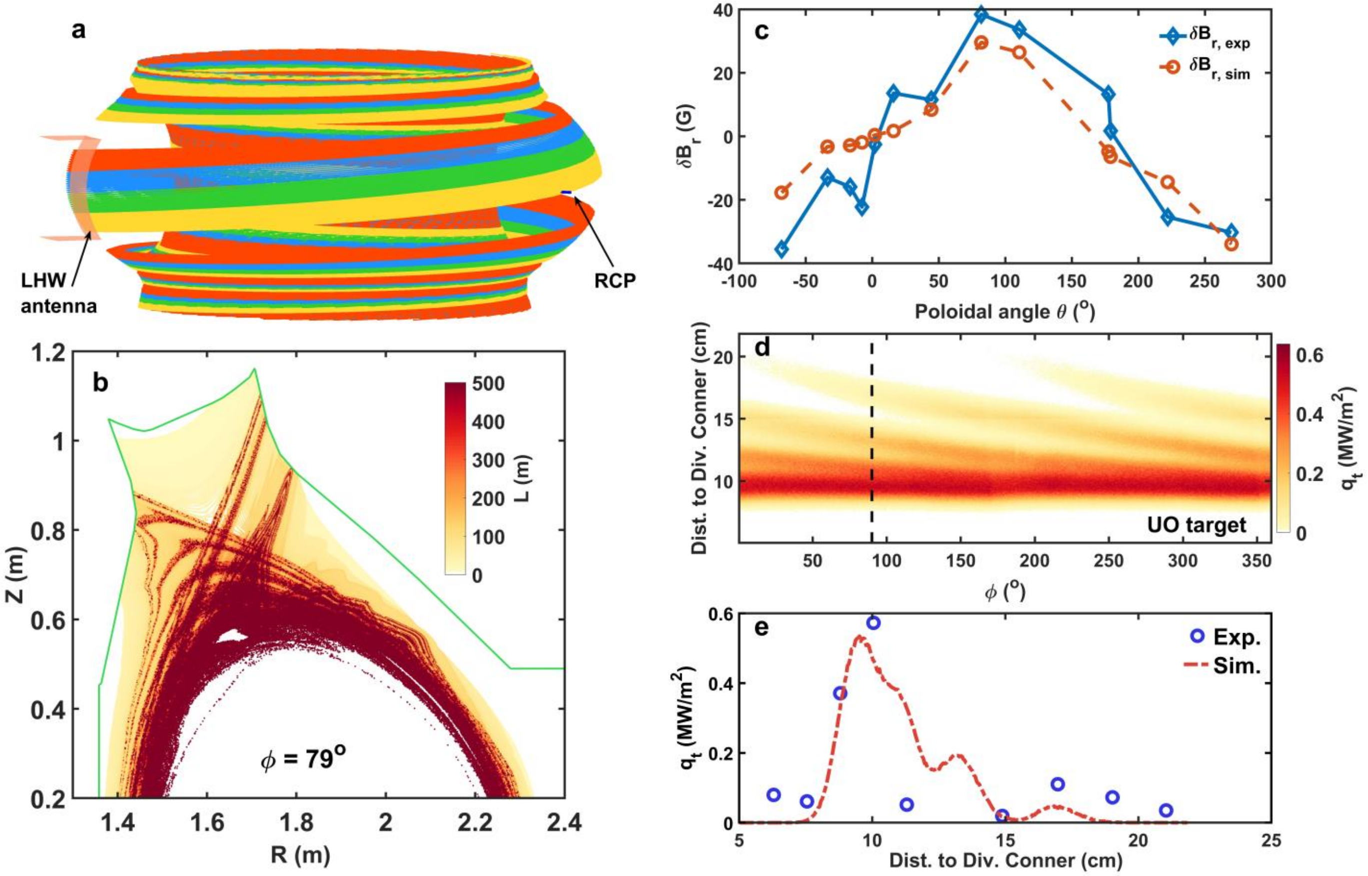






- ➢ Assume the amplitude of HCFs is the same on a magnetic flux surface in the front of LHW antenna.
- ➢ Build up LHW HCFs according to the radial profiles measured by DEP.

Validation of HCFs model with experiment



- $\tilde{B}_{r,exp} = B_{r,\,LHW\ on} - B_{r,LHW\ off}$ is measured by magnetic coils in experiment.
- Simulated perturbed magnetic field $\tilde{B}_{r,sim}$ agrees well with experimental $\tilde{B}_{r,exp}$.
- Simulated divertor heat flux is consistent with that measured by divertor Langmuir probe.
- Prove the HCFs model is accurate.

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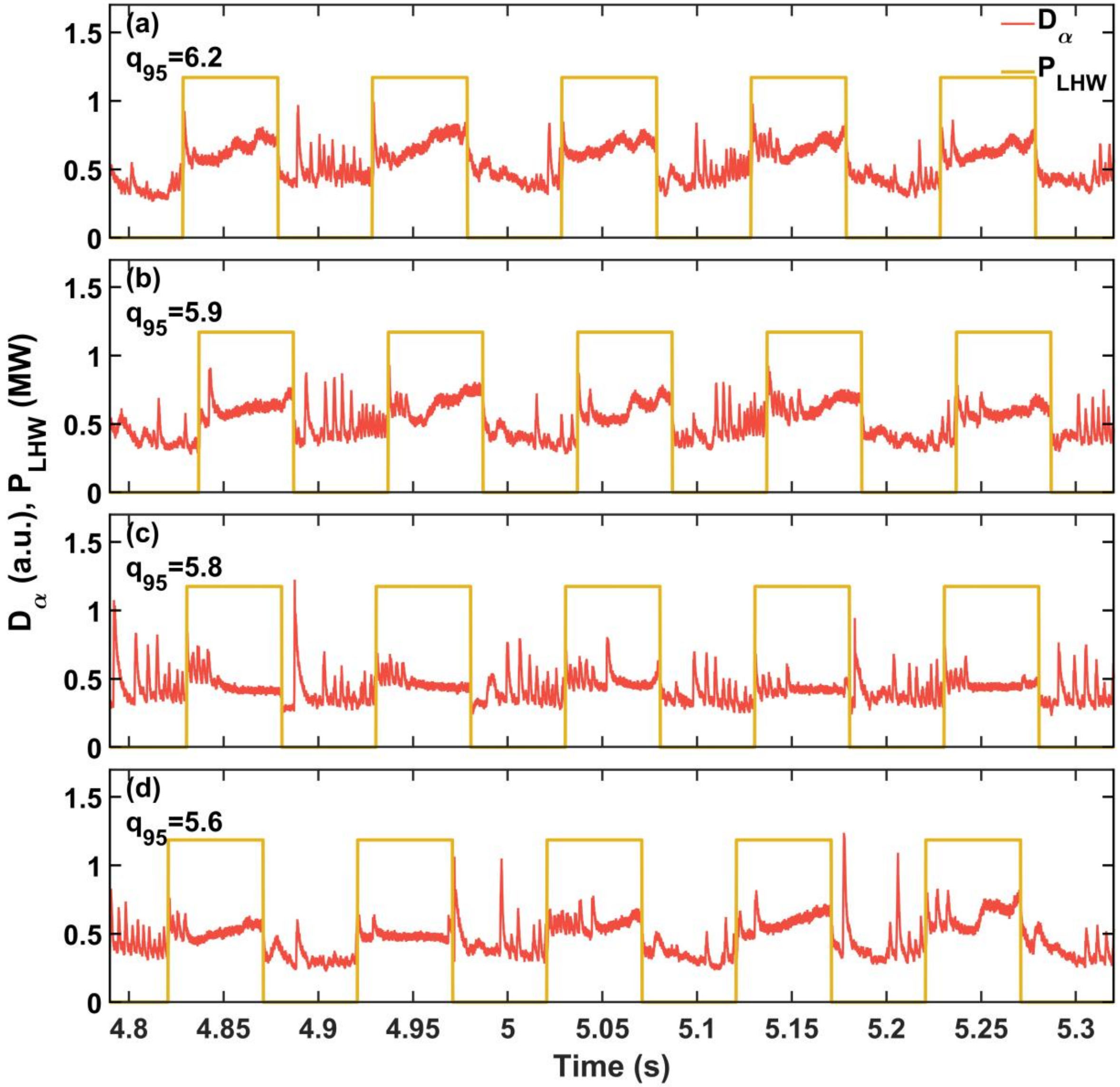
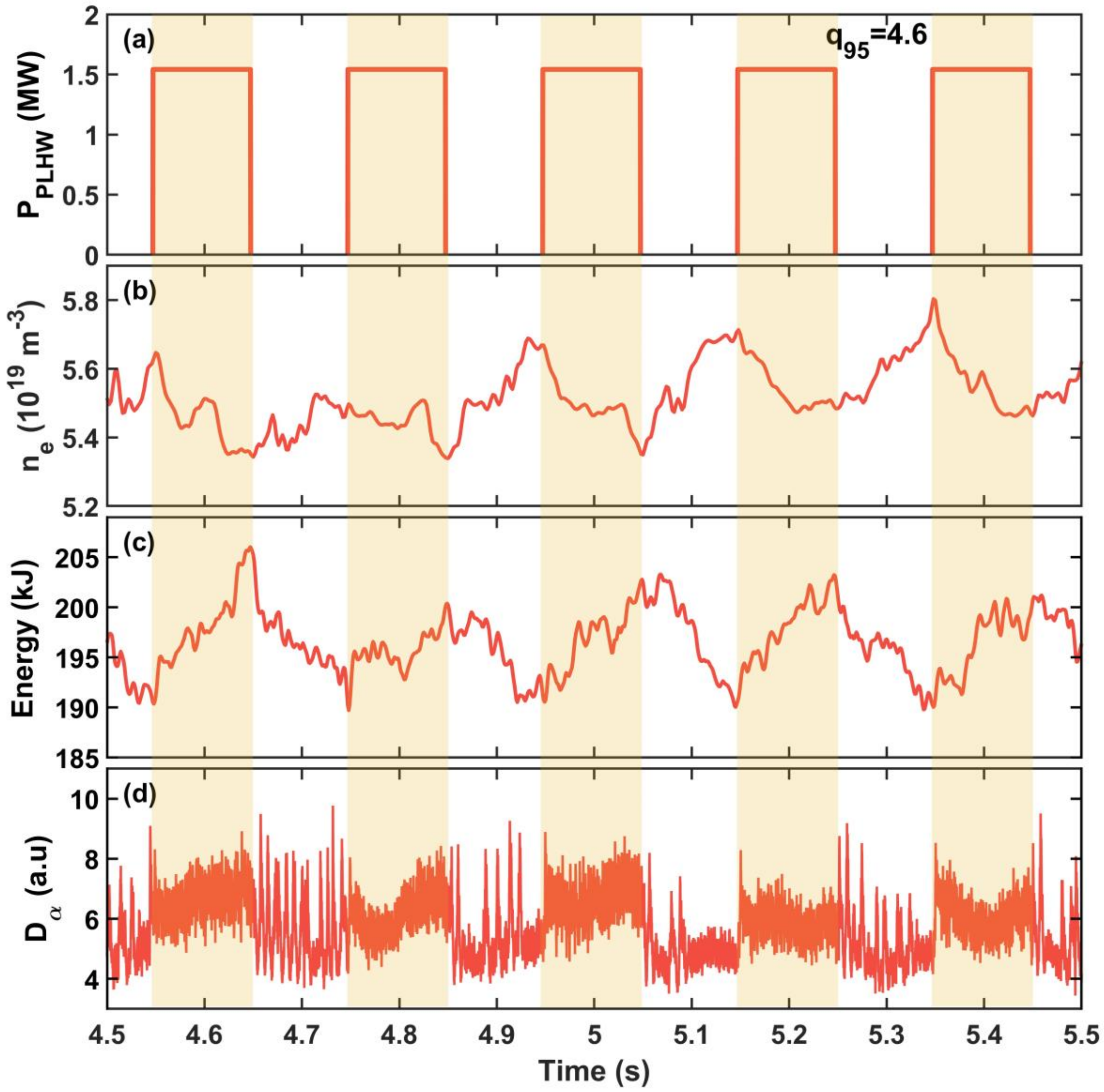
ELM control experiment with LHWs on EAST



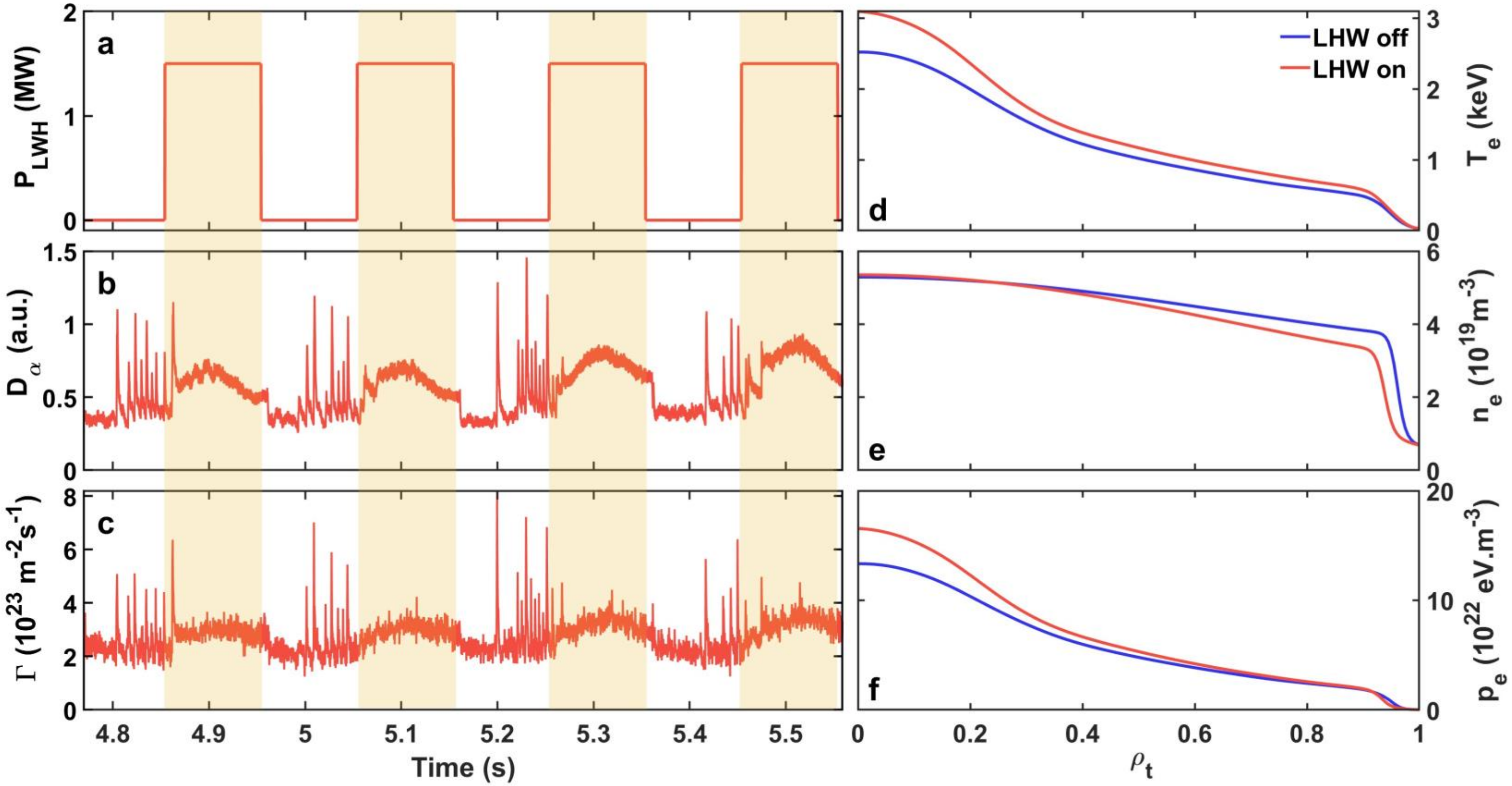
- ELM suppression with LHWs has been achieved on EAST in 2023.
- Obtain ELMy H-mode by using 1.4-2 MW ECRH and 1.5-2 MW NBI.
- Operate in high plasma density condition ($\bar{n}_e =$ 3.5-4.5×10^{19} m^{-3}) to raise the amplitude of HCFs.
- q_{95} = 5.2-6.2, B_{t0} = 2.7 T.
- $P_{LHW,4.6GHz}$ = 1-1.5 MW, modulated with 5-10 Hz frequency and 50% duty circle.

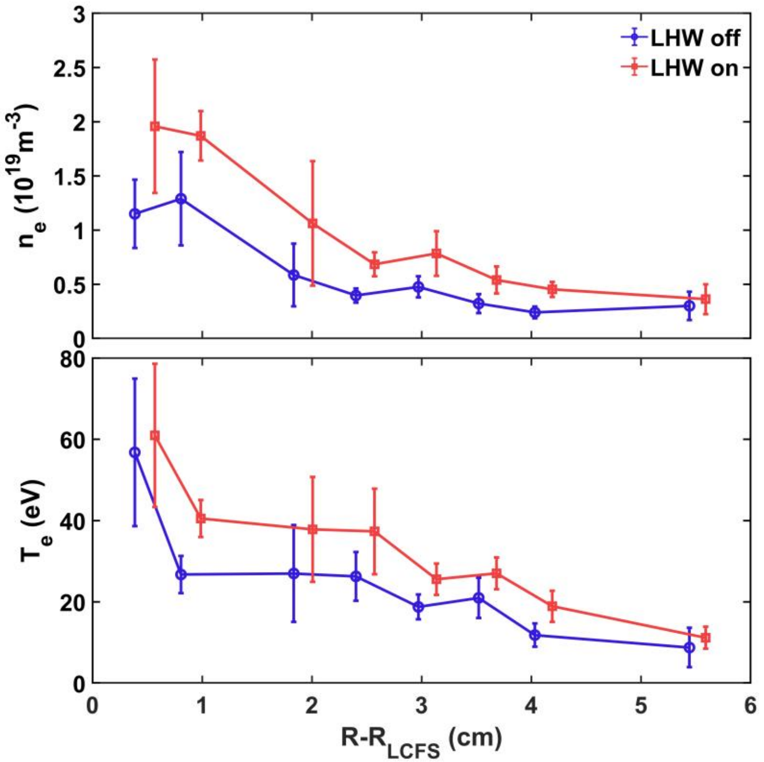
ELM control experiment with LHWs on EAST



- ➢ ELM suppression with LHWs and $q_{95} = 4.6$ has been achieved in 2025.
- ➢ Obtain ELMy H-mode by using 1.35 MW ECRH and 1.5 MW NBI.
- ➢ Higher plasma density ($\bar{n}_e = 5.5 \times 10^{19}$ m^{-3}) is required to suppress ELMs.
- ➢ $q_{95} = 4.6$-5.5, $B_{t0} = 2.7$ T.
- ➢ $P_{LHW,4.6GHz} =$ 1.5 MW, modulated with 5 Hz frequency and 50% duty circle.

ELM Suppression with LHW Modulation

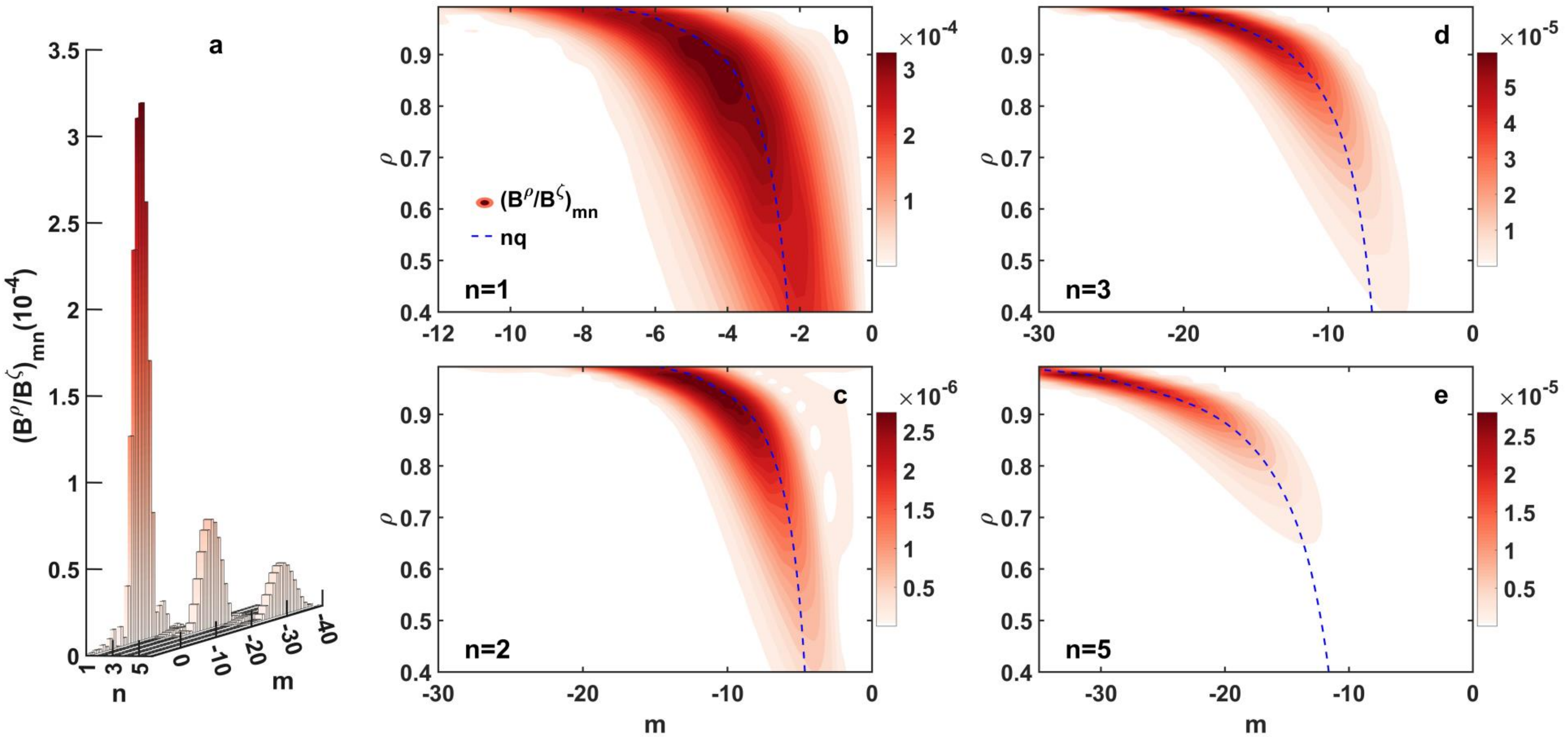




- $P_{LHW,4.6GHz}$ = 1.5 MW, modulation with 5 Hz frequency.
- ELM suppression is achieved when LHW is turned on with higher T_e and lower n_e in edge plasma.
- Enhanced divertor particle flux.

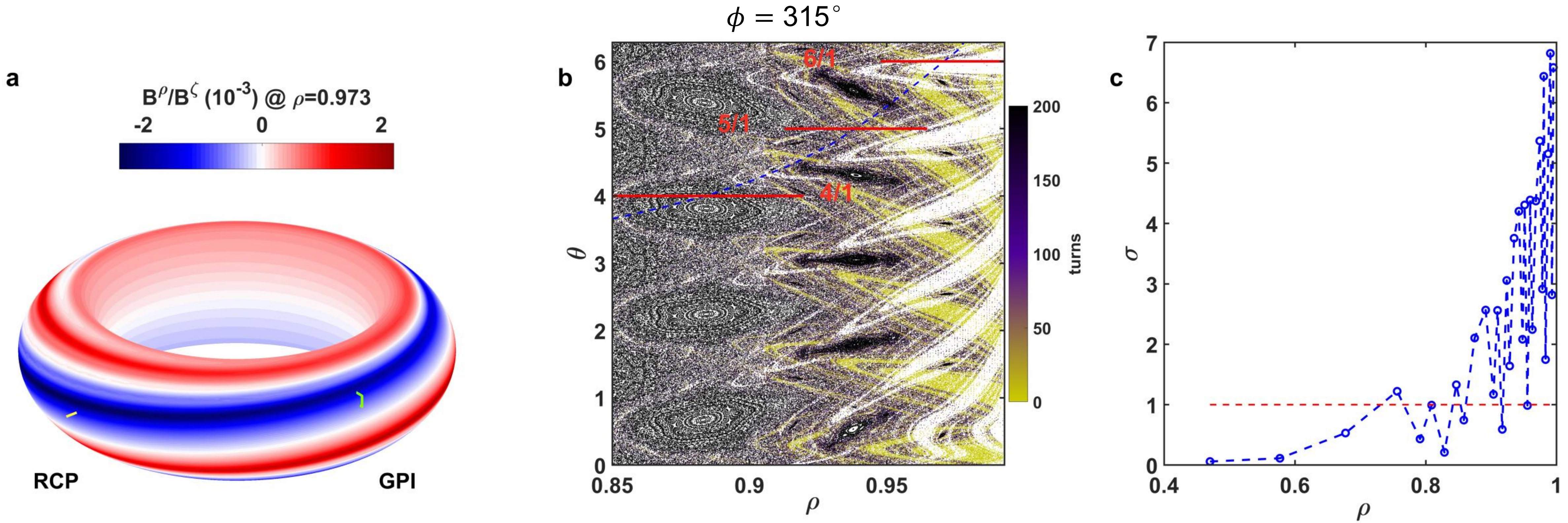
P_{ECRH} = 1.4 MW
P_{NBI} = 2.5 MW
P_{LHW} = 1.5 MW
$\bar{n}_e$ = 4.1-4.5×10^{19} m^{-3}
q_{95} = 5.7

Normalized Radial Magnetic Perturbation from HCFs Modelling



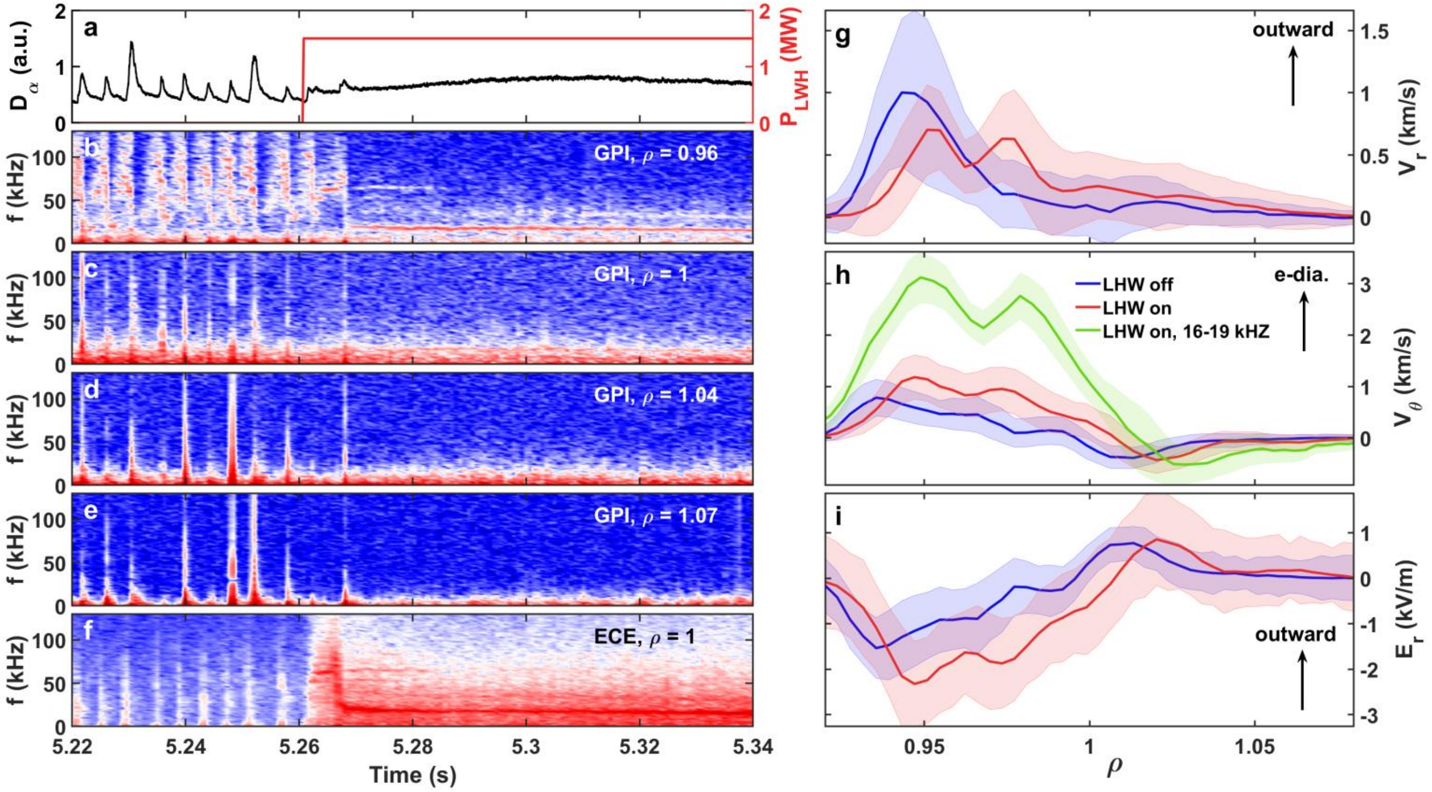
- The dominant perturbation component is $n = 1$.
- $n = 1$ component of normalized radial magnetic perturbation B^ρ/B^ζ is 3×10^{-4}.
- Good resonant spectrum for n =1, 2, 3, 5.

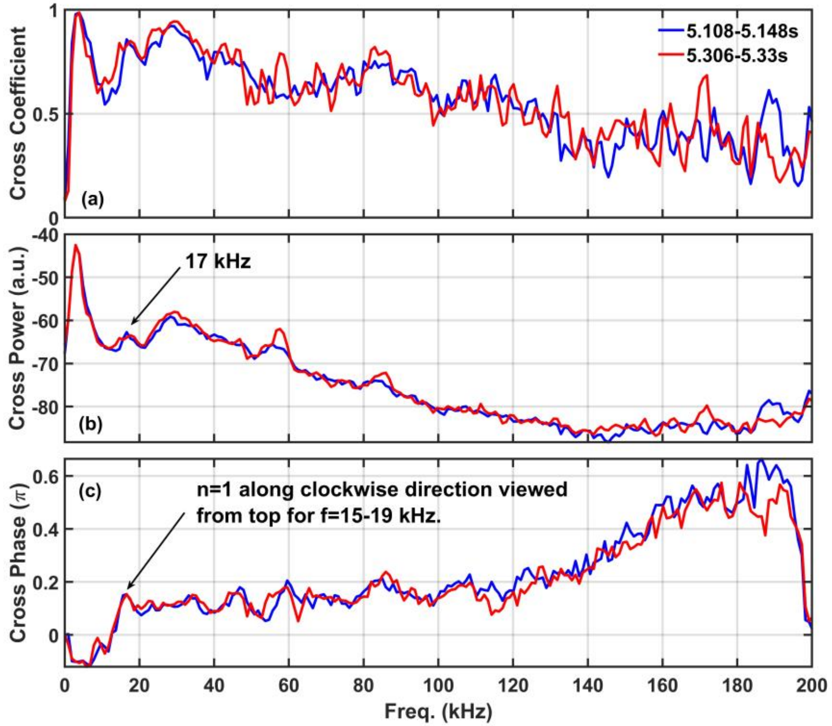
Edge Magnetic Topology from HCFs Modelling



- Magnetic islands are formed in edge plasma, with 5/1 islands at $\rho = 0.92 - 0.96$.
- Chirikov parameters is obviously larger than 1 when $\rho > 0.9$.

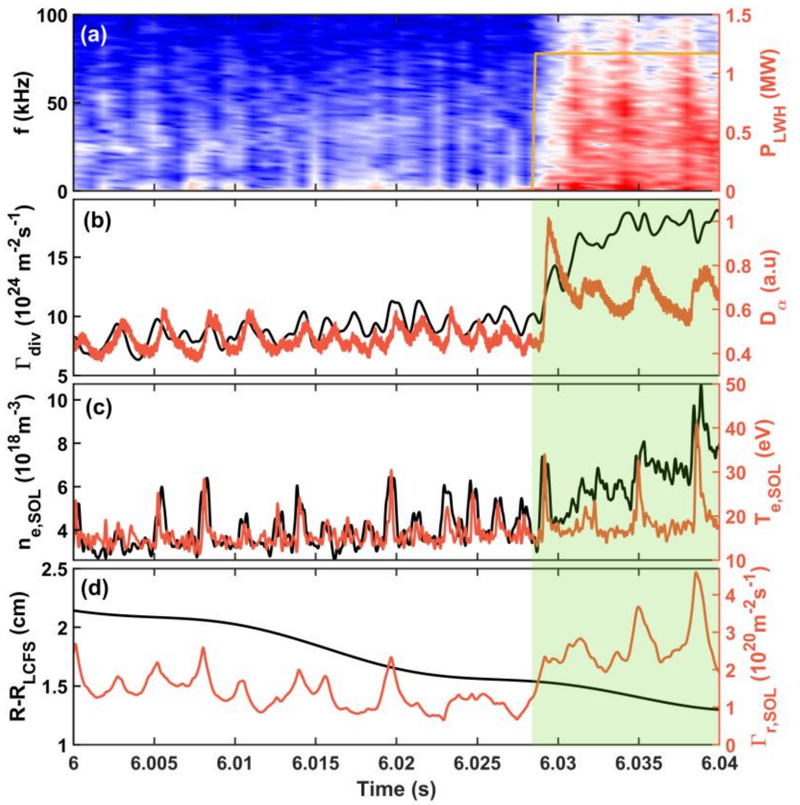
Edge Turbulence During ELM Suppression

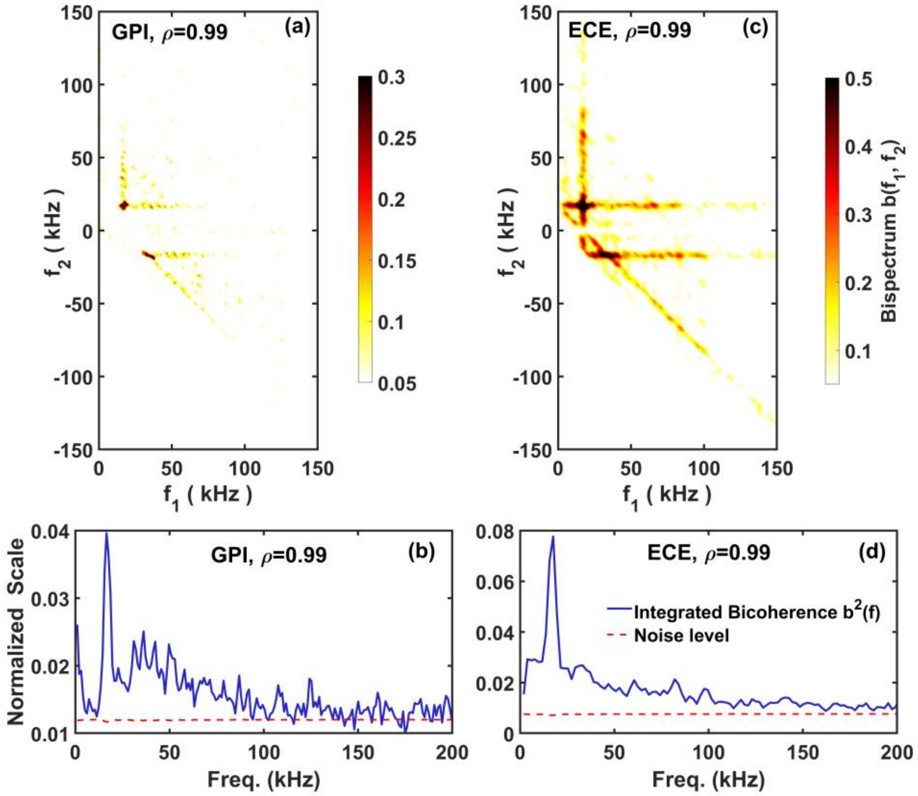


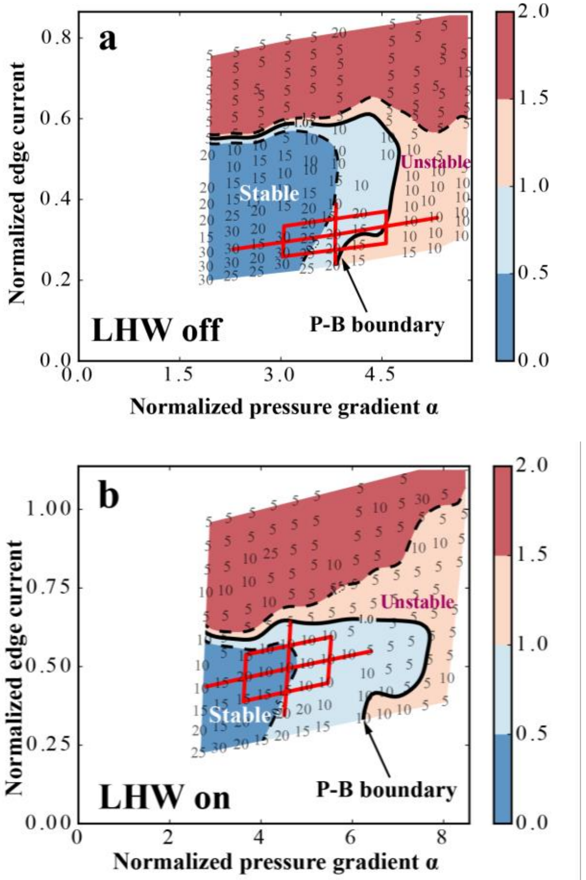


- An edge coherent mode (ECM) around 17 kHz is observed in the edge plasma and becomes weak in the SOL when ELM is suppressed, with $n = 1$ in clockwise direction viewed from top.
- Edge broadband turbulence is enhanced significantly during ELM suppression.

Edge turbulence transport and stability

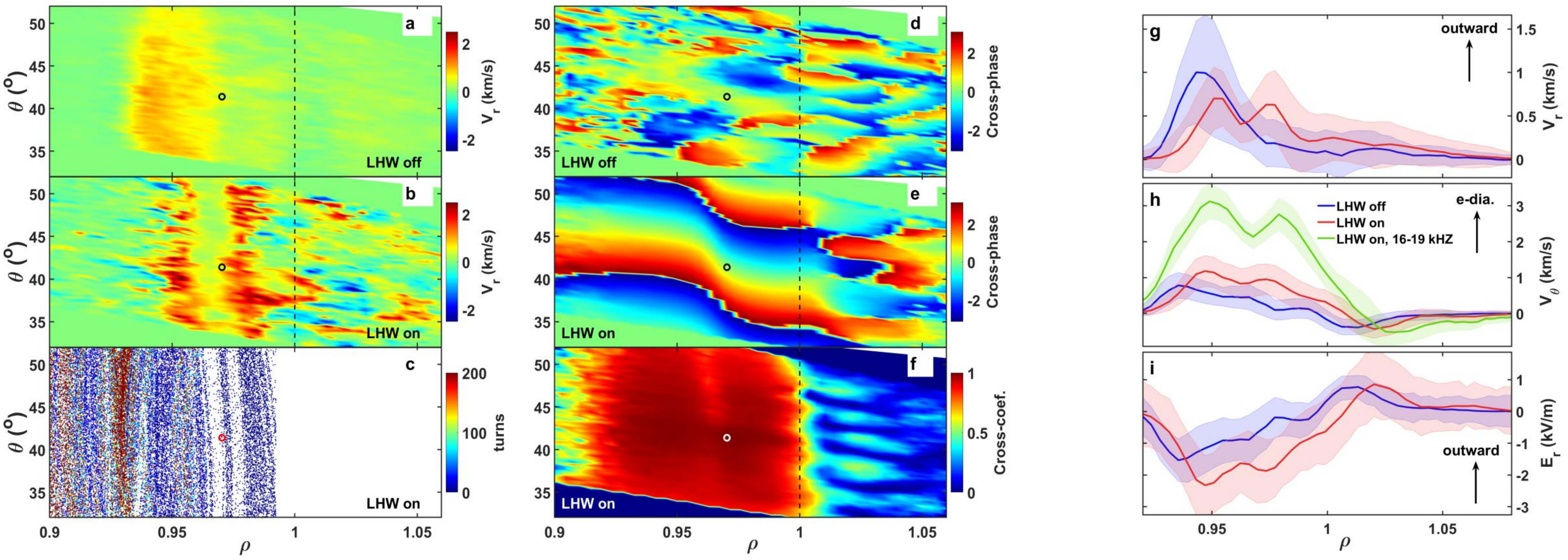






- Edge radial turbulence transport is enhanced when LHW is switched on.
- Strong three-wave interaction between the ECM and the broadband turbulence.
- Plasma is shifted from unstable region to stable region of P-B mode in ELM suppression.

Sheared structures of ECM in ELM suppression



- ➢ Strong sheared structures of ECM is observed in pedestal during ELM suppression, which aligns with the local magnetic topology.
- ➢ Indicating the formation of edge magnetic island and stochastical region caused by HCFs of LHW.

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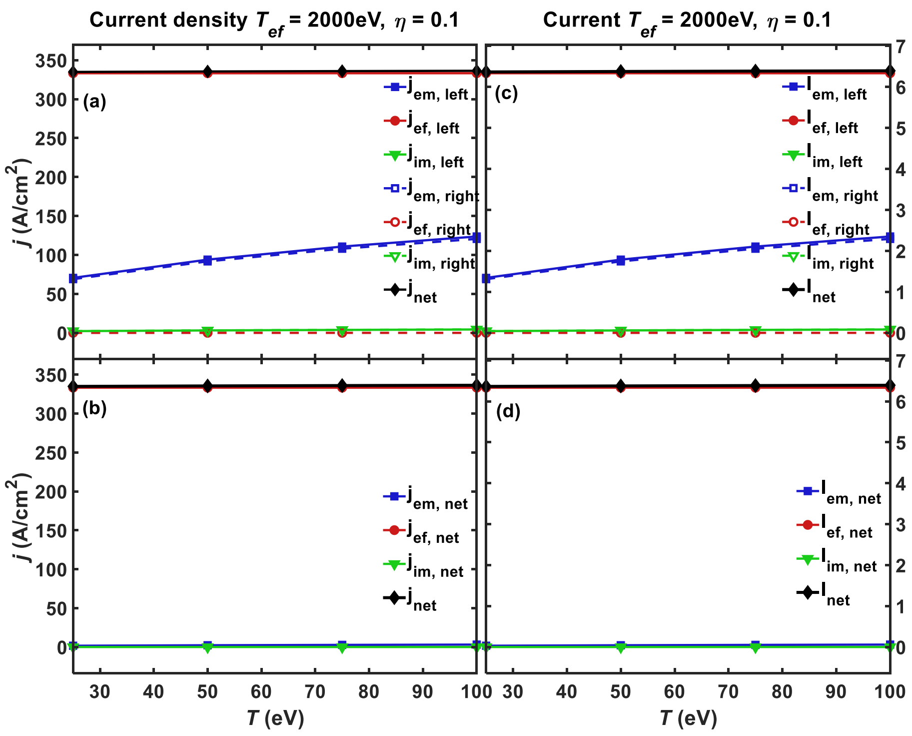
Summary

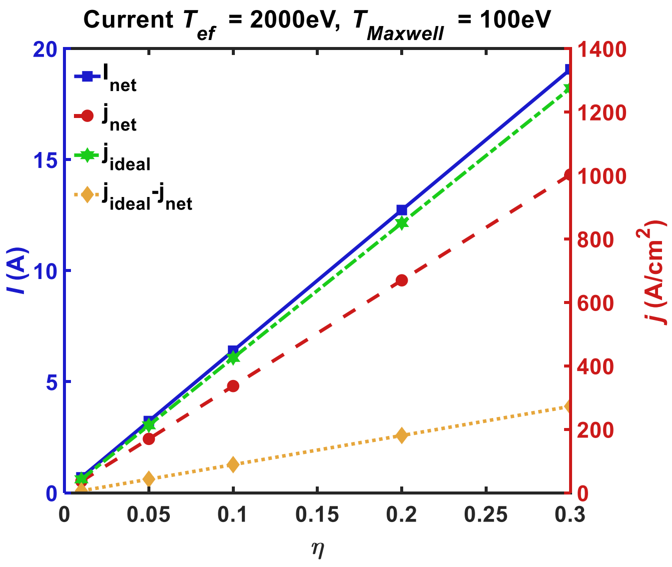
- The helical current filaments (HCFs) measured directly by DEP, covers a radial region over 20 mm in the SOL with a maximum current density around 20-30 A/cm^2; a clear density threshold is found for HCFs.
- HCFs model is built based on the profiles of HCFs measured by DEP; good agreement between the simulated perturbed magnetic field and the experimental observations of radial magnetic field perturbations and divertor heat flux footprints.
- ELM suppression is achieved by LHW in experiment, and the perturbed magnetic field reveals a good resonant spectrum in edge plasma according to the HCFs modelling.
- Edge radial transport is enhanced in ELM suppression with LHWs.
- Strong sheard turbulence structures is observed in pedestal in ELM suppression, indicating the formation of edge magnetic island or stochastical region caused by HCFs of LHW.

Thank you for your attention!

Collected Current Analysis

n_{em} = 1×10^{19} m^{-3} $n_{ef} = \eta n_{em}$ $n_i = n_{em} + n_{ef}$ $T_{em} = T_i$





$$I_{im} = \sum_{p_l} \iiint e n_i v_y A_l f(v_x, v_y, v_z) h(p_l, v_x, v_y v_z) dv_x dv_y dv_z$$

$$I_{im} = \sum_{p_l} \iiint e n_i A_l h(p_l, v, \theta\phi) \left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} e^{-\frac{m}{2kT}v^2} v^3 sin\theta cos\theta dv d\theta d\phi$$

$$I_{ef} = \sum_l e n_{ef} v_{ef} A_l g(p_l, v_{ef})$$

$$I_{total} = I_{em} + I_{ef} - I_{im}$$

$$I_{net} = I_{right} - I_{left}$$

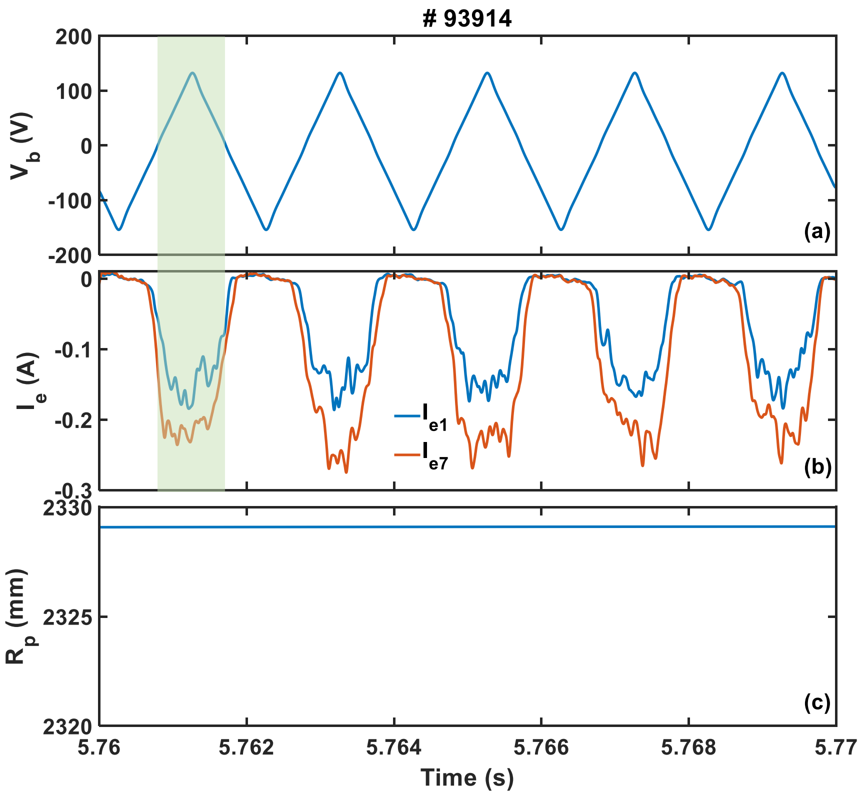
$$j_{im} = I_{im}/S$$

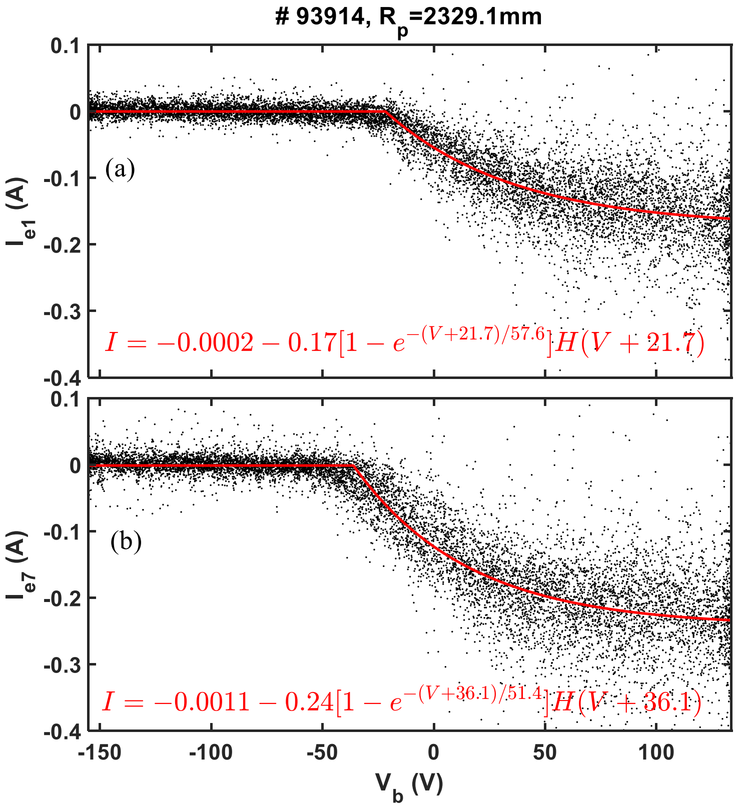
$$j_{ef} = I_{ef}/S$$

$$j_{net} = I_{net}/S$$

- Non-thermal electrons are injected only on the right side.
- Thermal ion/electron collected currents of both sides agree well with each other, but the ion current is negligible.
- Net current is contributed by non-thermal electrons.

Experimental Verification





$$I(V) = I_{01} + I_{02}\left[1 - e^{-\frac{(V-V_0)}{V_a}}\right]H(V - V_0)$$

$$H(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases}$$

$n_{el} = 5 \times 10^{19}$ m^{-2}

$P_{LHW} = 1$ MW

$q_{95} = 4$

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- Swept biasing voltage from -150 to +130 V with frequency 500 Hz.
- Very weak existence of super thermal electrons with extremely high T_e.
- Strong asymmetry of collected current when V_b is positive enough.