The simulations on the edge instabilities of the RF heating H-mode discharges on EAST

Presenter: T.Y. Xia[1*]

Y.L. Li[1,2], Y.Q. Huang[2,3], B. Gui[1], Y.B. Wu[1,4,5], Y.M. Wang[1], X.L. Zou[6], X.J. Zhang[1], C. Zhou[2], D.F. Kong[1], Y. Ye[1], Z.H. Qian[1], Q. Zang[1], M.Q. Wu[1], Y.Q. Chu[1], G.H. Hu[1], S.F. Mao[2], M.Y. Ye[2] and EAST Team[1]

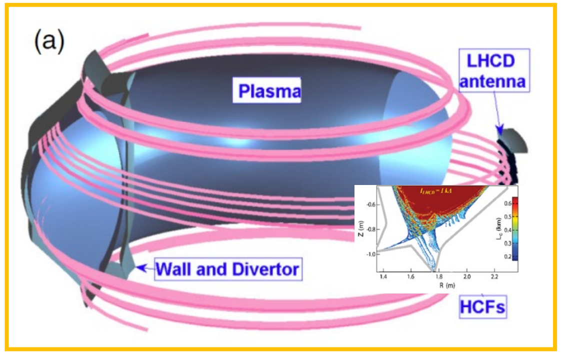
Collaborated with: X.Q. Xu, B. Zhu at LLNL

[1]ASIPP, [2]USTC, [3]Hengyang Normal University, [4]Donghua University, [5]Anqing Normal University, [6]CEA,

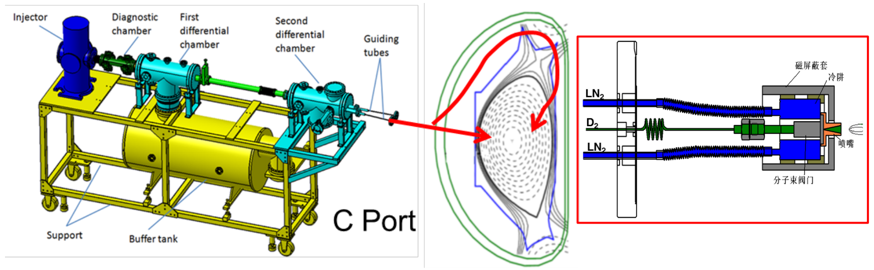
***E-mail: xiaty@ipp.ac.cn**

*This work was supported by National Key R&D Program of China under Grant No. 2017YFE0301100, 2017YFE0301101, and 2014GB106001. The China Natural Science Foundation under Contract No.11675217 and 11505236. This work is also sponsored in part by Youth Innovation Promotion Association Chinese Academy of Sciences (2017479) and K.C. Wong Education Foundation. Numerical computations were performed on the ShenMa High Performance Computing Cluster in Institute of Plasma Physics, Chinese Academy of Sciences.

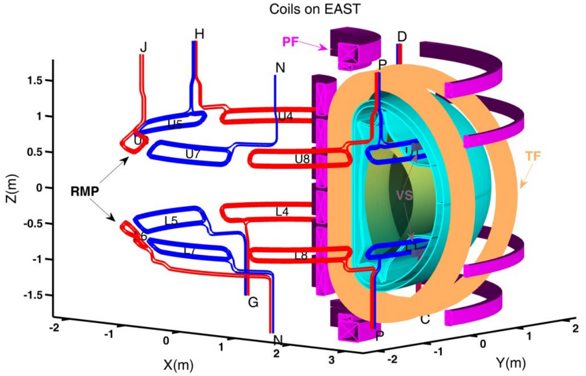
Various effective ELM control methods on EAST



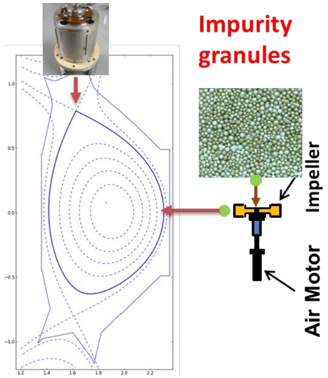
Lower Hybrid wave (LHW) [Liang Y. *et al*, PRL (2013)]



Pellet, super-sonic molecular beam injection (SMBI)



Resonant magnetic perturbation[Sun Y. *et al*, PRL (2016)]



Lithium injection [Hu J. *et al*, PRL (2015)]

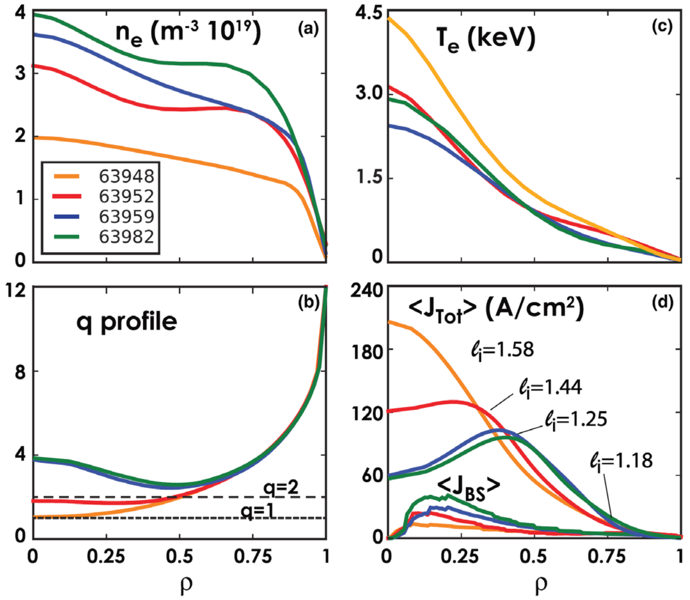
- ➢ EAST is the tokamak which can be operated under the ITER-like long-pulse, low rotation and metal wall conditions.
- ➢ Various ways of ELM control have been developed on EAST successfully.

ASIPP

The effects of RF waves on edge instabilities

➢Indirect effects:

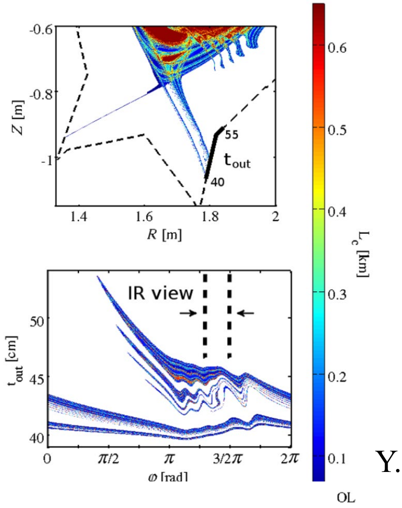
- ☐ Heating: profiles
- ☐ Current driving: magnetic shear
- ☐ Ponderomotive force: rotation
- ☐ …



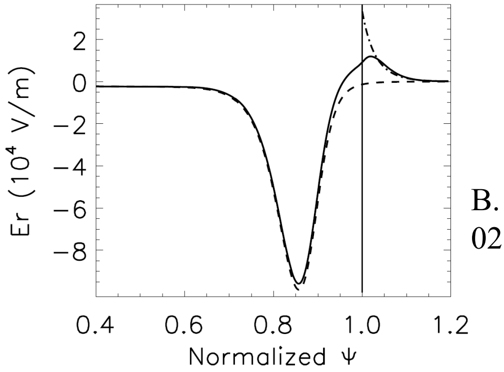
A. Garrofallo et al., NF 57 076037 (2017)

➢Direct effects:

- ☐ Current driving: topology
- ☐ RF sheath: SOL rotation
- ☐ Source terms
- ☐ …



Y.F. Liang et al., PRL 110, 235002 (2013).



B. Gui et al., NF 58 026027 (2018)

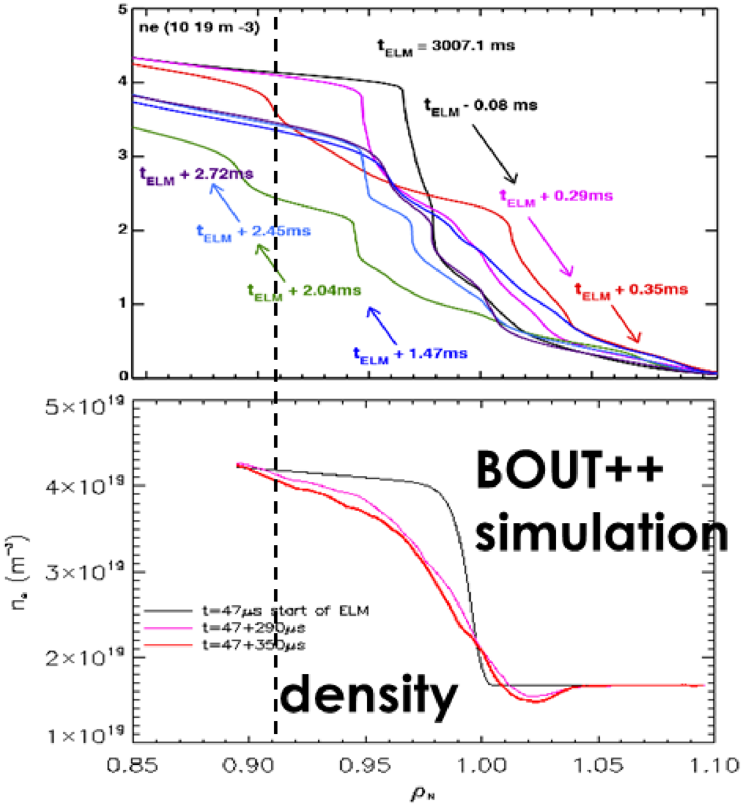
$$m_s n_s\left(\frac{\partial \mathbf{V}_s}{\partial t}+\mathbf{V}_s\cdot\nabla\mathbf{V}_s\right)=n_s q_s(\mathbf{E}+\mathbf{V}_s\times\mathbf{B})-\nabla p_s -\nabla\cdot\pi_s+\mathbf{R}_s\boxed{+\mathbf{F}^{\mathrm{rf}}_{s0},}$$

$$\frac{3}{2}n_s\left(\frac{\partial T_s}{\partial t}+\mathbf{V}_s\cdot\nabla n_s\right)+n_s T_s\nabla\cdot\mathbf{V}_s=-\nabla\cdot\mathbf{q}_s-\pi_s:\nabla\mathbf{V}_s+Q\boxed{+S^{\mathrm{rf}}_{s0}.}$$

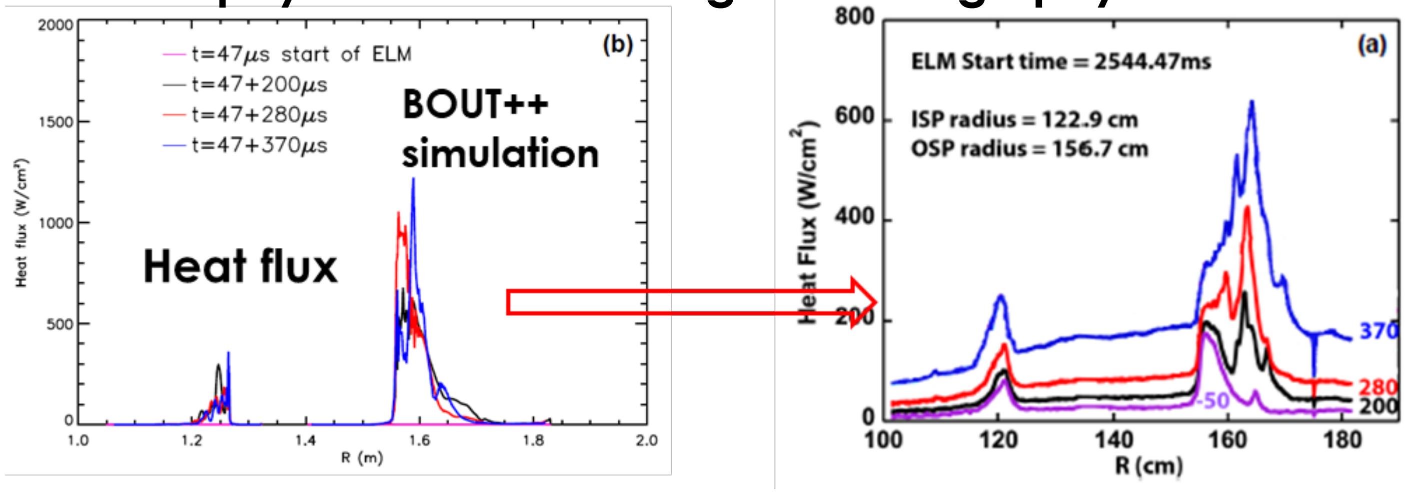
C.C. Hegna & J.D. Callen, PoP 16, 112501 2009

BOUT++ framework has been used to reproduce the profile change & transient fluxes induced by edge instabilities

The 6-field 2-fluid model is widely used on the physics understanding of the edge physics for tokamaks

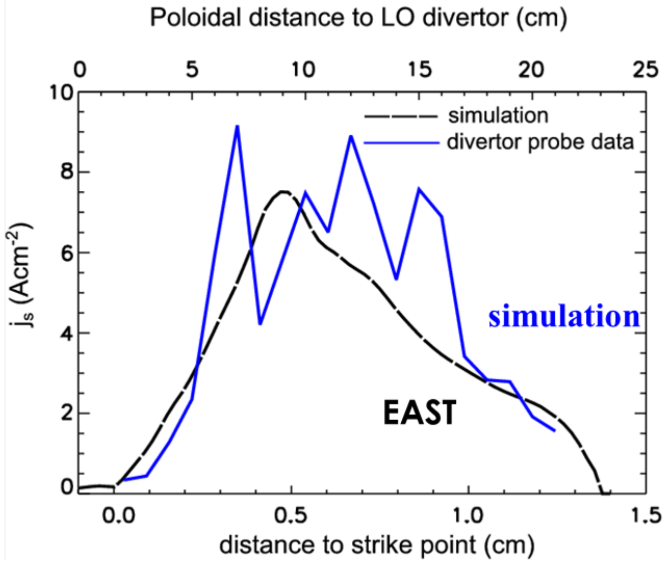


Density evolution during ELM on DIII-D



Transient heat flux during ELM on DIII-D

T.Y. Xia, et al. Nucl. Fusion, 55 (2015) 113030



Transient particle flux by ELM on EAST

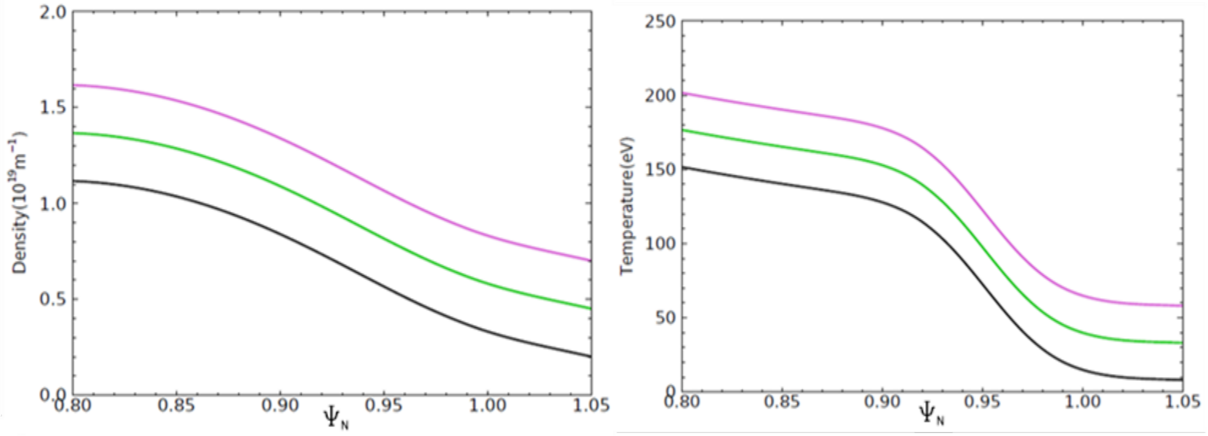
Y.B. Wu, T.Y. Xia et al., PCF 60 (2018) 055007

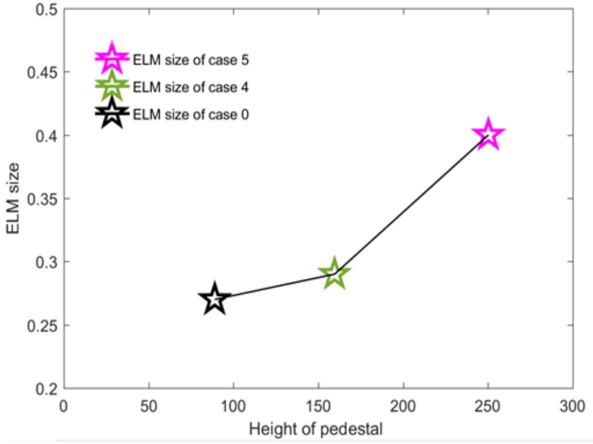
Outline

- ➢Indirect effects by RF:
  - ☐ Pedestal scan for ELM
  - ☐ Edge turbulence and the interactions with ELM
- ➢Direct effects by RF:
  - ☐ HCF effects on the turbulence & heat flux
  - ☐ RF sheath on ELM

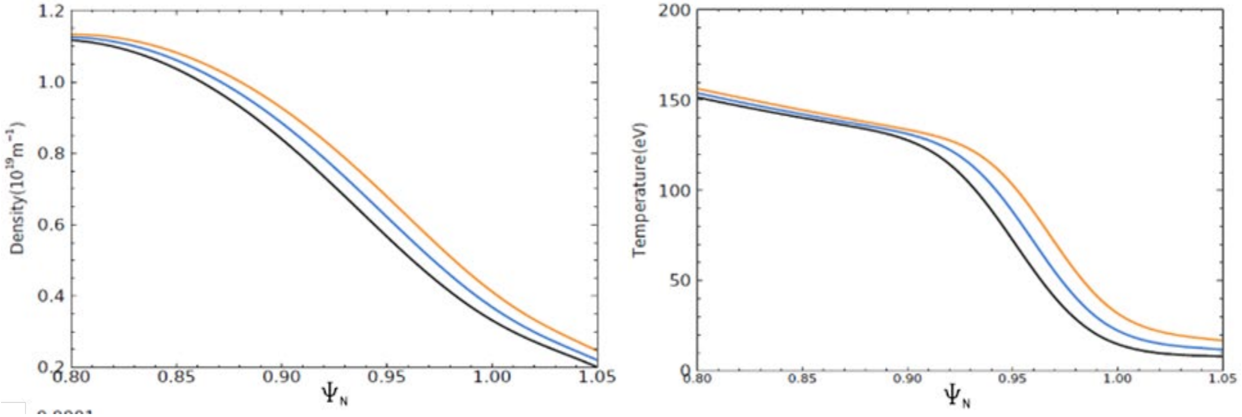
The effects of RF heating on ELMs: pedestal scans

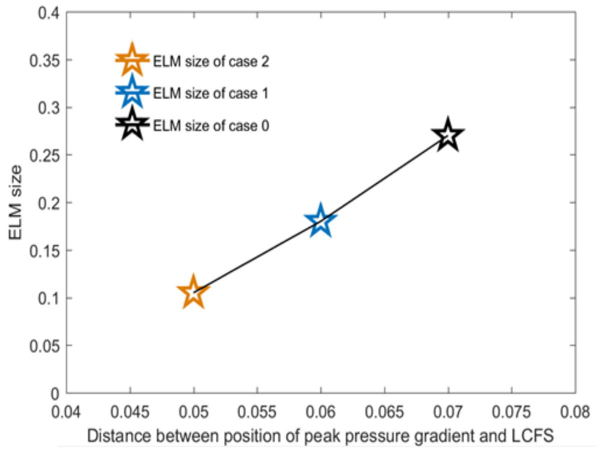
- **The change of the pedestal height: The higher pedestal, the larger ELM size**



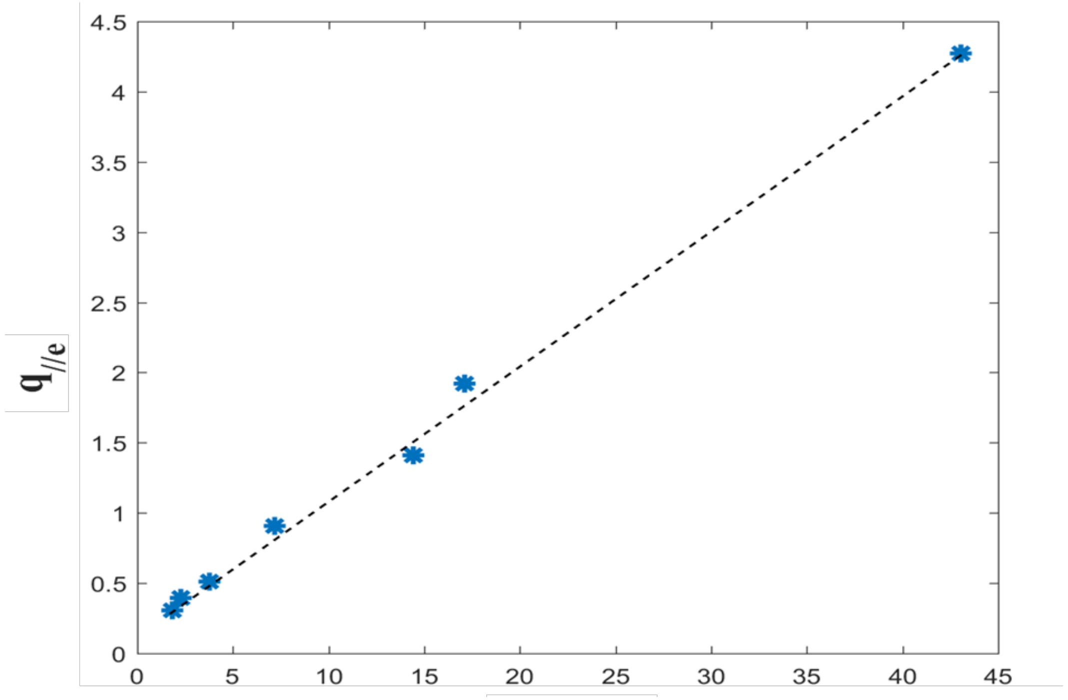


- **The change of the pedestal position: The closer of the pedestal to separatrix, the smaller ELM size**





The peak divertor heat flux is proportional to the upstream density & temperature



$n_{e0\_SEP}T_{e0\_SEP}{}^{3/2}$

Effective thermal conduction in 6-field 2-fluid module of BOUT++

$$\kappa_{\mathrm{eff},j} = \frac{\kappa_{\parallel j}\kappa_{\mathrm{fs},j}}{\kappa_{\parallel j} + \kappa_{\mathrm{fs},j}}$$

$$\kappa_{\mathrm{fs},j} = n_j v_{\mathrm{th},j} q R_0$$

$$q_{\parallel e} \simeq 0.235 n_{e0,SEP} T_{e0,SEP}^{\frac{3}{2}}$$

- **The peak divertor heat flux induced by ELM is proportional to $n_{e0\_SEP}T_{e0\_SEP}{}^{3/2}$**
- **The free-streaming expression is used in the flux-limited expression of the parallel thermal conduction (T.Y. Xia et al., NF 2013)**

X.X. He, et al., Accepted by AIP Advances

ASIPP

Outline

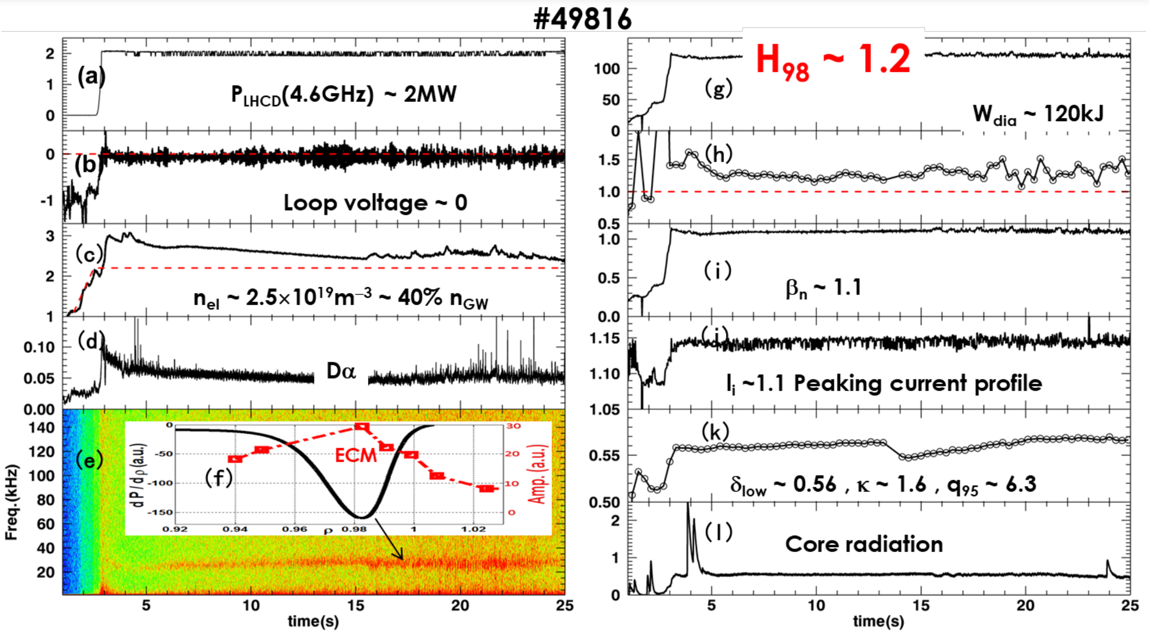
- Indirect effects by RF:
  - ☐ Pedestal scan for ELM
  - ☐ **Edge turbulence and the interactions with ELM**
- Direct effects by RF:
  - ☐ HCF effects on the turbulence & heat flux
  - ☐ RF sheath on ELM

ASIPP

The frequency and poloidal wavenumber of the coherent mode at EAST pedestal are reproduced by the simulations

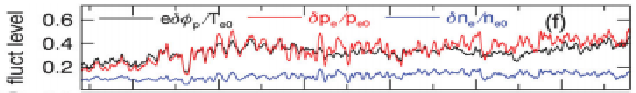
Validations on coherent mode:

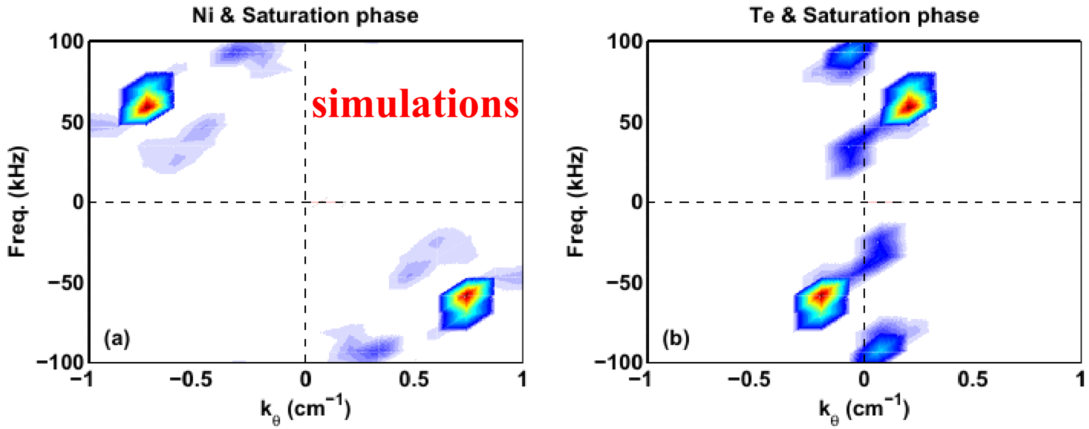
- Similar calculation of f and k
- Simulated frequency is close to exp.
- k_θ is in the range of exp. (0.5-0.7cm^{-1})
- Density fluctuations rotate in the electron diamagnetic direction
- The simulated fluctuations are in the similar amplitude with exp.

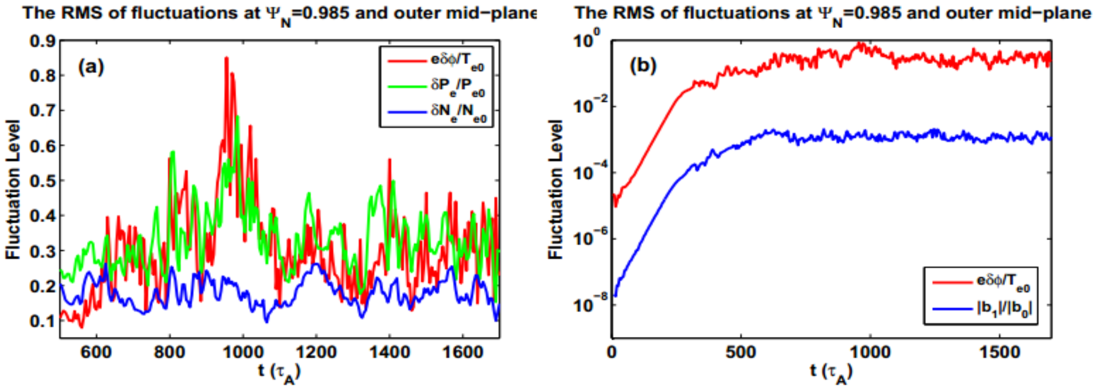


H. Q. Wang, et al., PRL, 112 185004 (2014)

EAST diagnostic

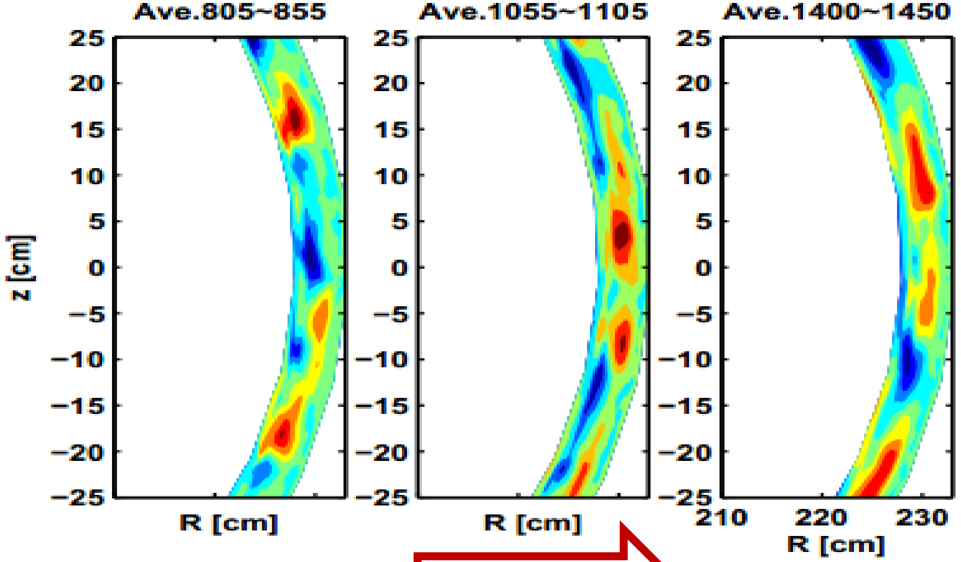






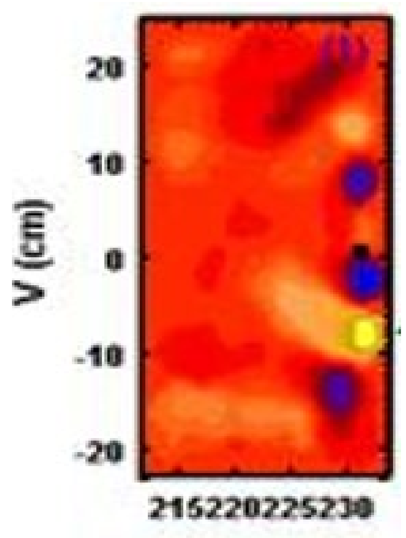
The simulated poloidal mode structures qualitatively agree with ECEI diagnostic

simulations



Early nonlinear phase → Saturation phase

ECEI



- The simulated toroidal mode structure shows the similar numbers
- The radial extension is narrower due to the noise of diagnostic (M. Kim, NF 2014)
- The poloidal extension is longer, smaller Te wavenumber in simulation.

The mode coupling leads to the generation of the coherent mode

Bicoherence:

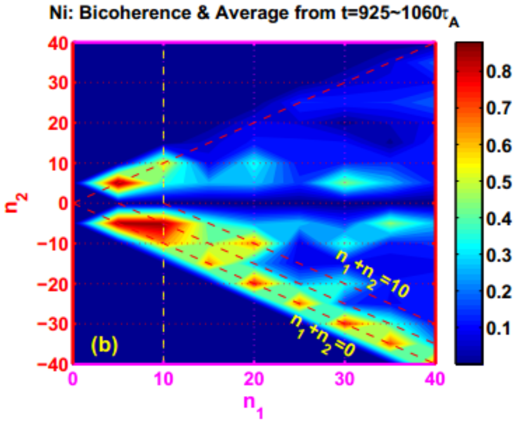
$$S(n_1,n_2) = Y^*(n_3)Y(n_1)Y(n_2),\ n_3 = n_1 + n_2.$$

$$b(n_1,n_2) = \frac{|S(n_1,n_2)|}{\sqrt{|Y(n_3)|^2}\sqrt{|Y(n_1)Y(n_2)|^2}}$$

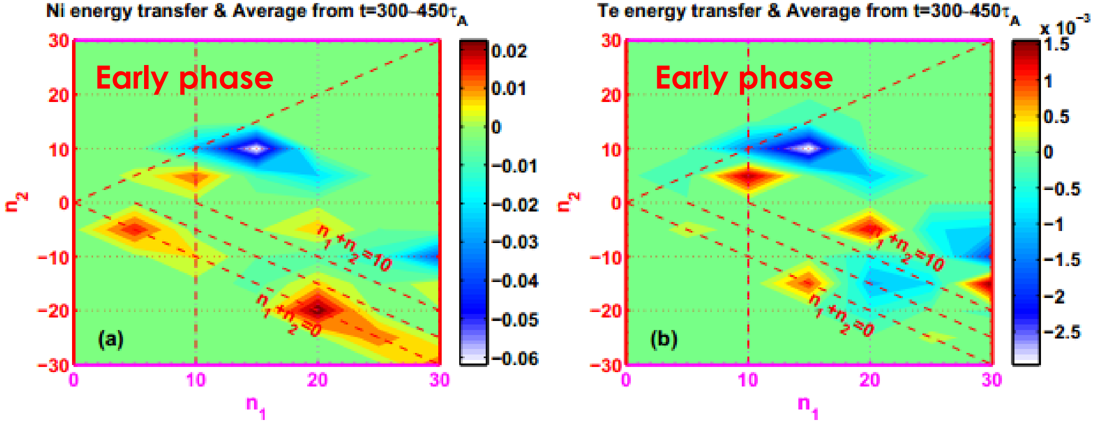
$$\frac{\partial\varphi(k,t)}{\partial t} = \Lambda_k^L\varphi(k,t) + \sum_{k_1\geq k_2,k=k_1+k_2}\Lambda_k^Q(k_1,k_2)\varphi(k_1,t)\varphi(k_2,t)$$

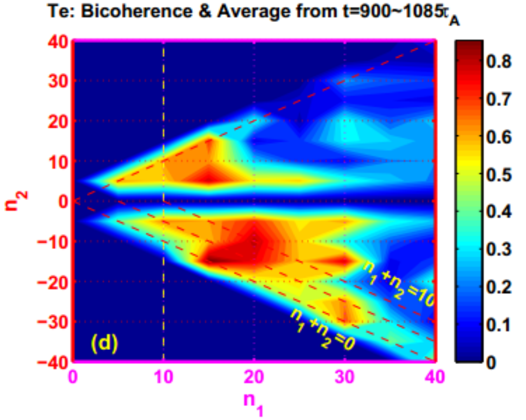
Energy transfer rate*:

$$\frac{\partial P_k}{\partial t} \approx \gamma_k P_k + T_k, \qquad P_k = <\varphi_k\varphi_k^*>$$

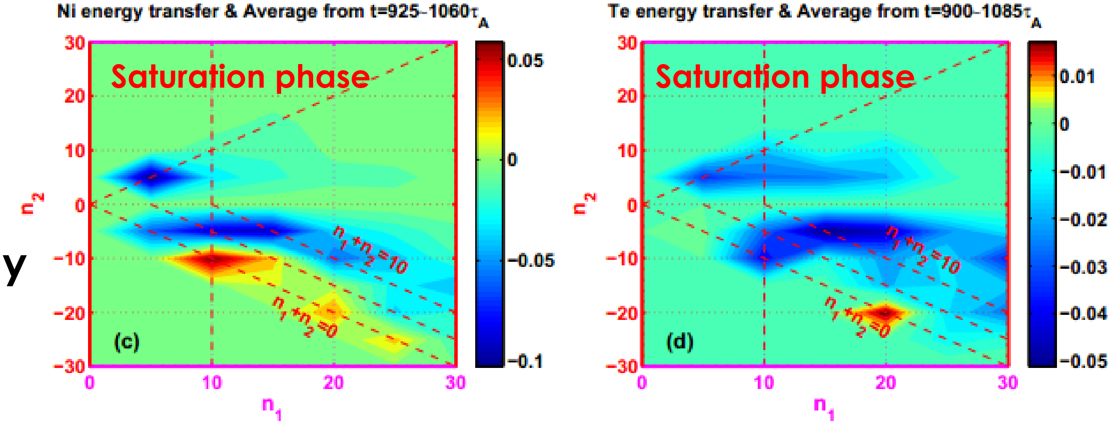


- Early nonlinear phase:
  Ni: more modes coupled to n=0 then n=15
  Te: more modes coupled to n=15 then n=0





- Saturation phase:
  Ni: lower n modes coupled to n=0
  Te: n=0 mode mostly from (20,-20)



Y.Q. Huang, et al., 2020 Nucl. Fusion 60 026014

*Kim J. S. et al 1996 Physics of Plasmas 3 3998

The coherent modes at pedestal are able to mitigate ELM

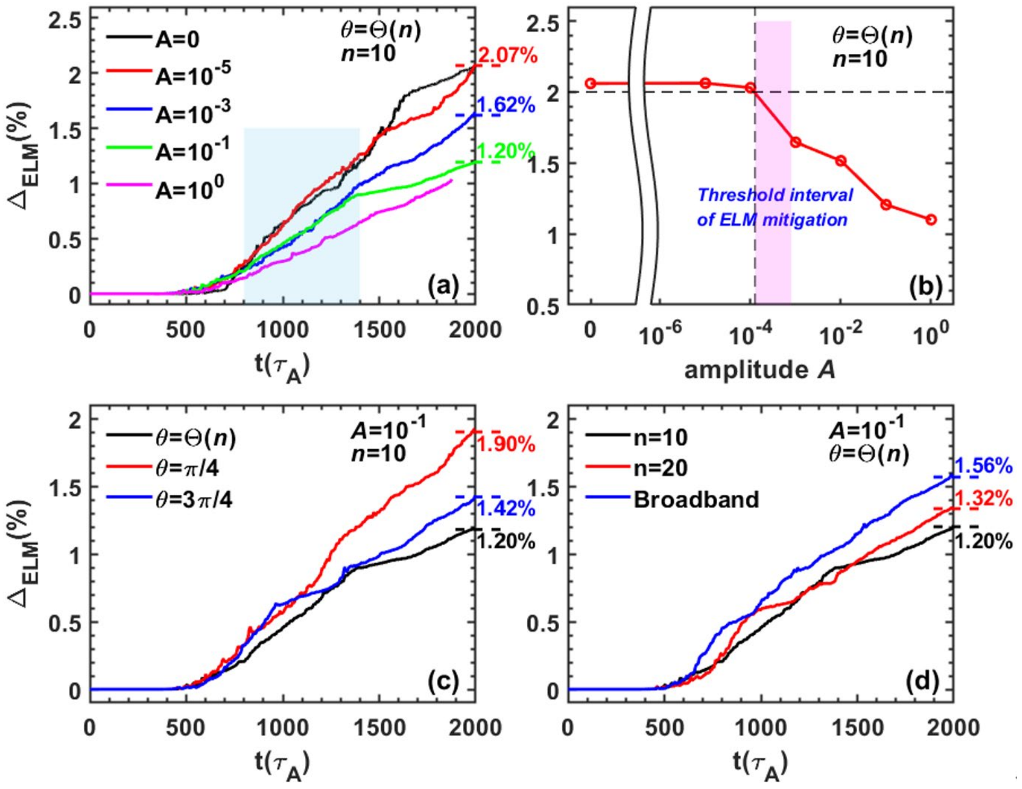
- **A modeled pedestal coherent mode (PCM) is added in BOUT++ to simulate the interactions with ELM.**

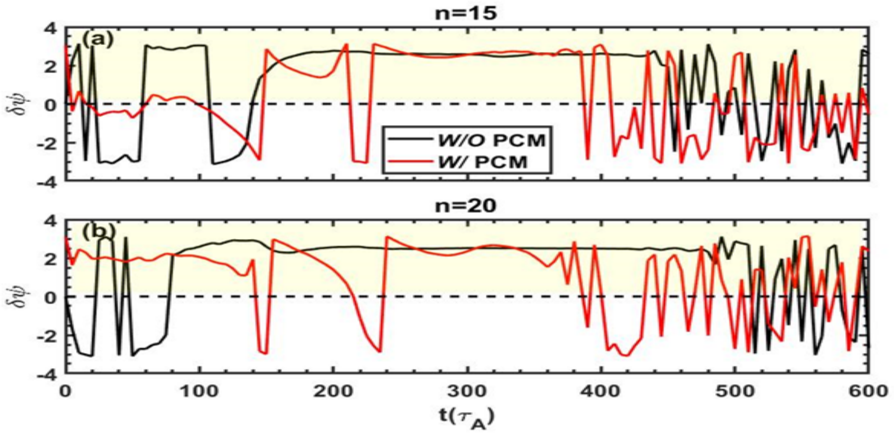
$$\tilde{P}_{PCM}(x,y,z,A) = Af(z)\cdot e^{\frac{(x-b_1)^2}{2\sigma_x^2}-\frac{(y-b_2)^2}{2\sigma_y^2}}.$$

$$f(z) = [F(n,\theta)]_{IFFT}.$$

$$\tilde{P}_{PCM}(x,y,z,A) = A\cdot e^{-\frac{(x-b_1)^2}{2\sigma_x^2}-\frac{(y-b_2)^2}{2\sigma_y^2}}\left[P_{kz}(n)e^{-i\theta}\right]_{IFFT}.$$

- **A threshold of the amplitude of PCM is found for ELM mitigation**
- **Phase angle and dominant toroidal mode can also affect ELM.**





- **The phase coherent time* is changed by the nonlinear wave-wave interactions in the linear phase, which change the growth time of the ELM.**

Y.L. Li et al., submitted to NF

***P.W. Xi, X.Q. Xu and P.H. Diamond, 2014 PRL 112**

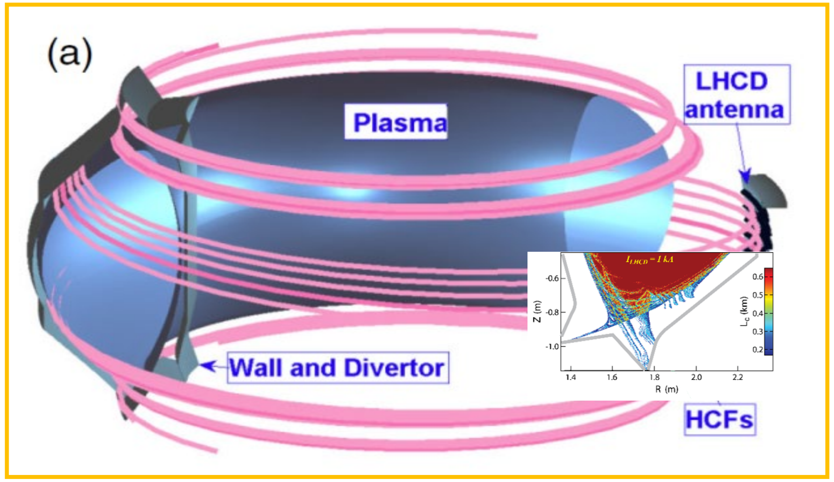
ASIPP

Outline

- ➢Indirect effects by RF:
  - ☐ Pedestal scan for ELM
  - ☐ Edge turbulence & heat flux validations
- ➢Direct effects by RF:
  - ☐ HCF effects on the turbulence & heat flux
  - ☐ RF sheath on ELM

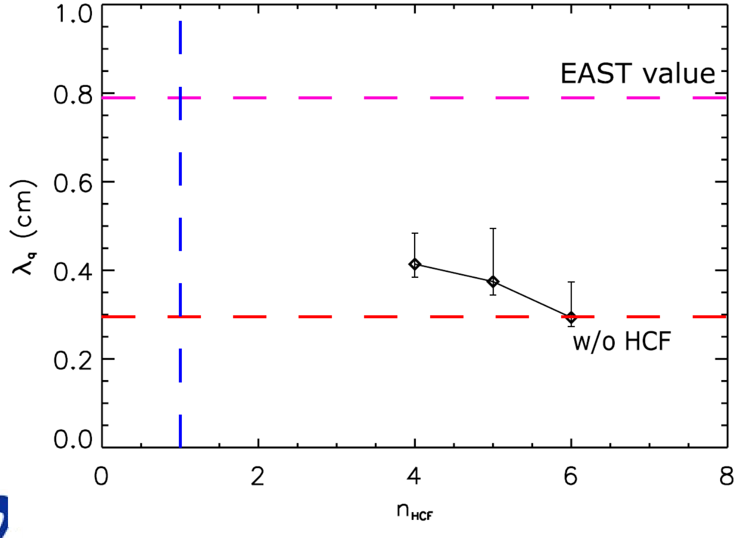
ASIPP

The simulations reproduce the splitting of the strike point by helical filamentary current (HCF)



Y.F. Liang et al., PRL 110, 235002 (2013).

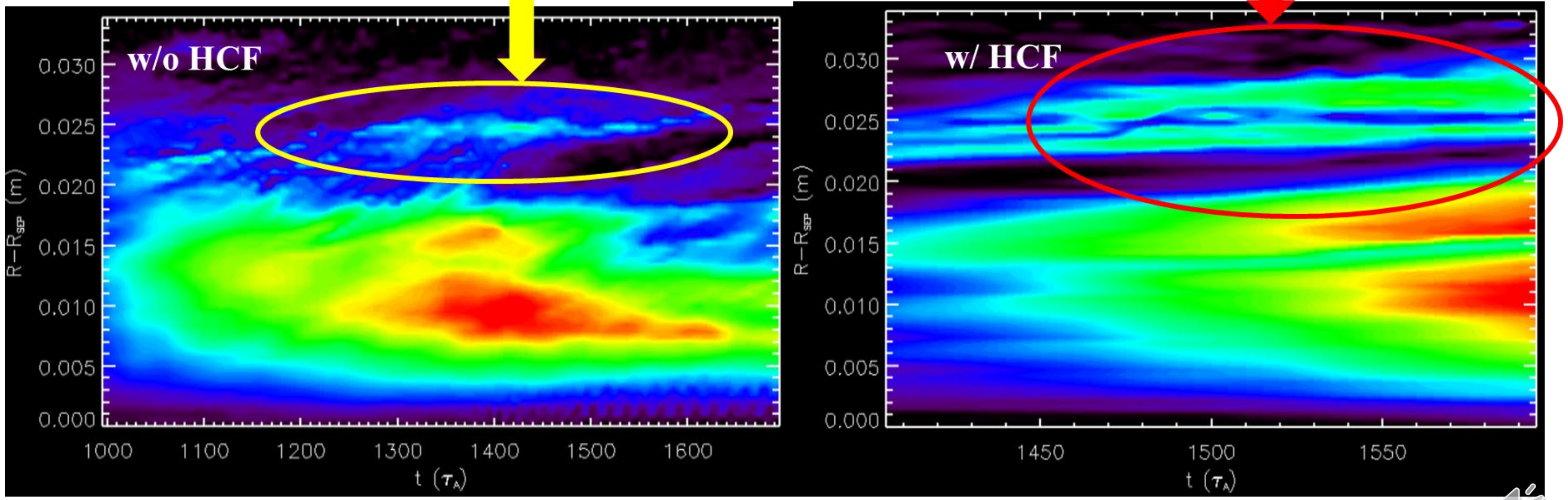
- A modeled HCF with force-free form in SOL is added into BOUT++ as the extra magnetic flutter.
- HCFs dominated by n=1, but n>1 used in the simulation due to the efficiency
- SOL width λ_q is indeed broadened by HCFs
- The splitting of strike point behavior is reproduced



HCF broadens SOL width

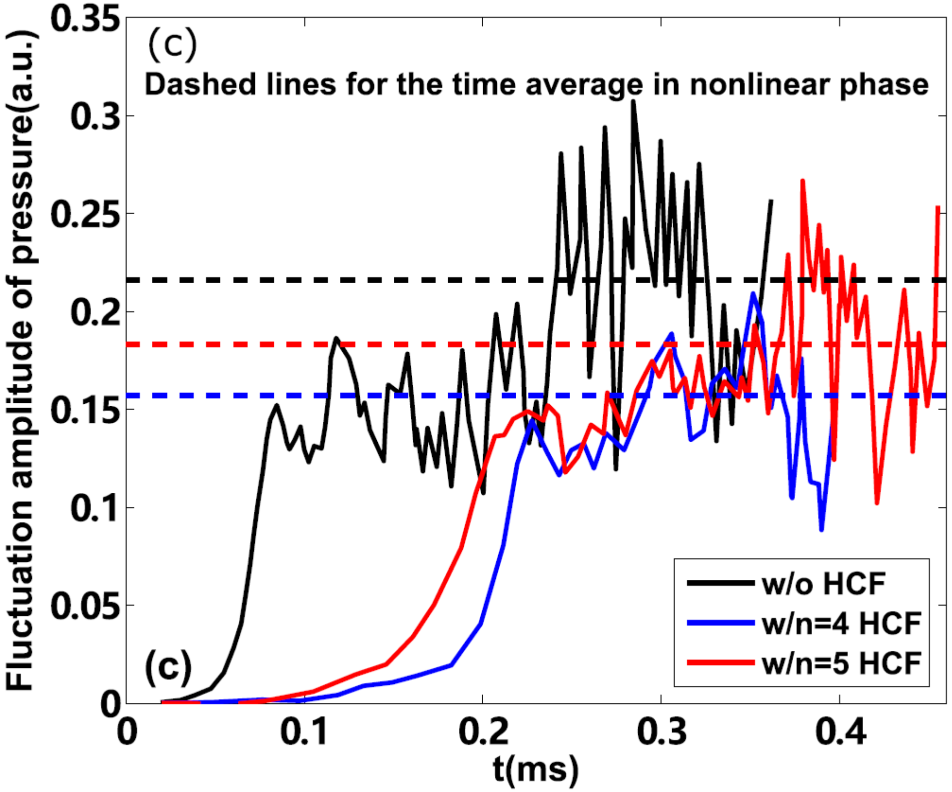
Weak filament align magnetic field line

Strong filament by HCF



T.Y. Xia et al., NF 59 076043 (2019)

The simulation proves that LHW can mitigate the edge turbulence effectively through the HCFs

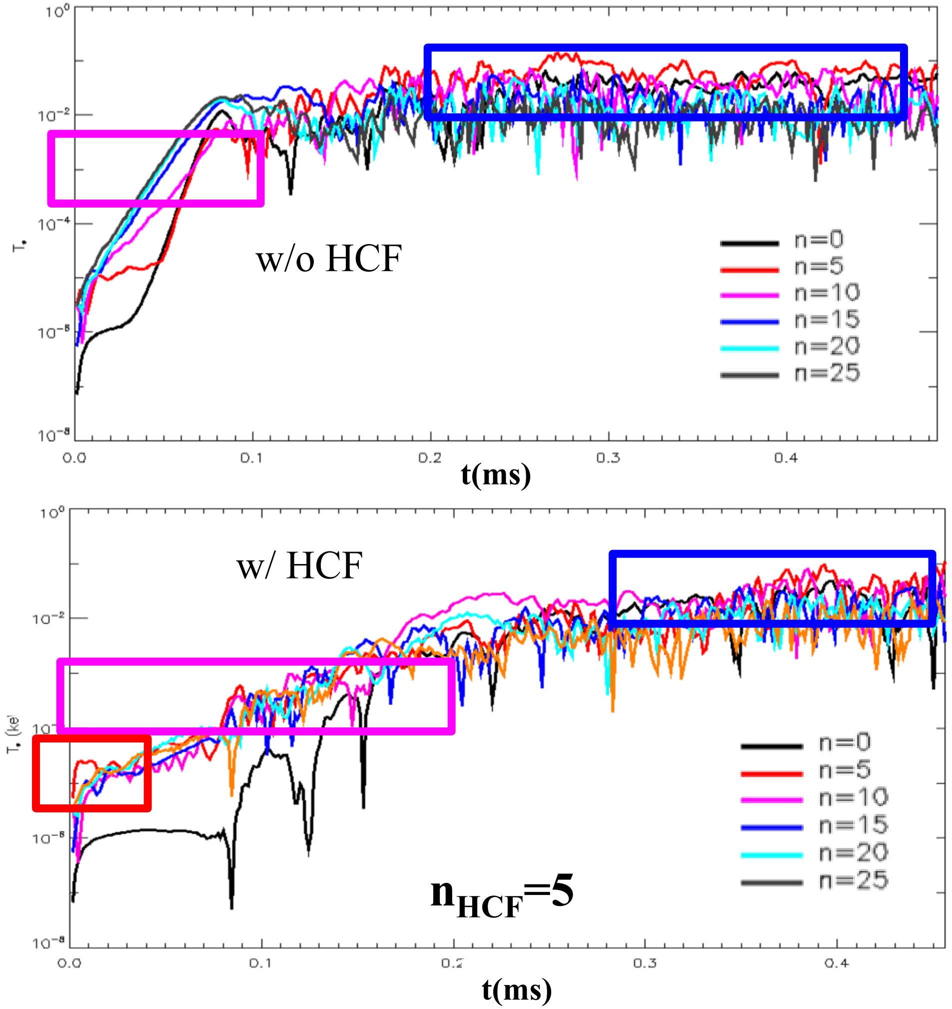


- ➢ The amplitude of fluctuation is decreased by HCF → mitigation of ELM
- ➢ HCF with lower n shows more obvious mitigation on fluctuations

ASIPP

The HCF induced Br decreases the linear growing of the fluctuations

- At linear phase, the dominant mode w/ HCF is decreased towards the number of HCF
- At late nonlinear phase, the dominant modes are the same.
- **The linear growing is mitigated by Br induced by HCF.**
- Nonlinear mode interactions among multi modes driven by HCF Br decrease the phase coherent time (P.W. Xi, PRL, 2014) and leads to the slow growing.



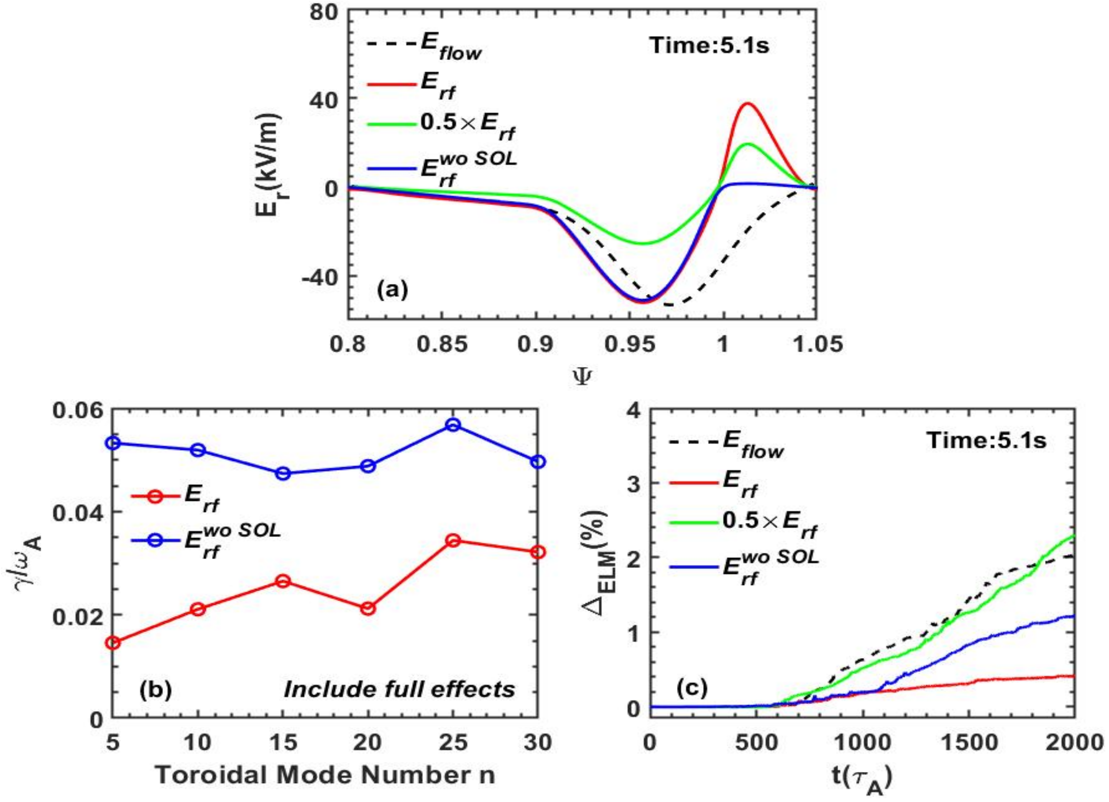
Outline

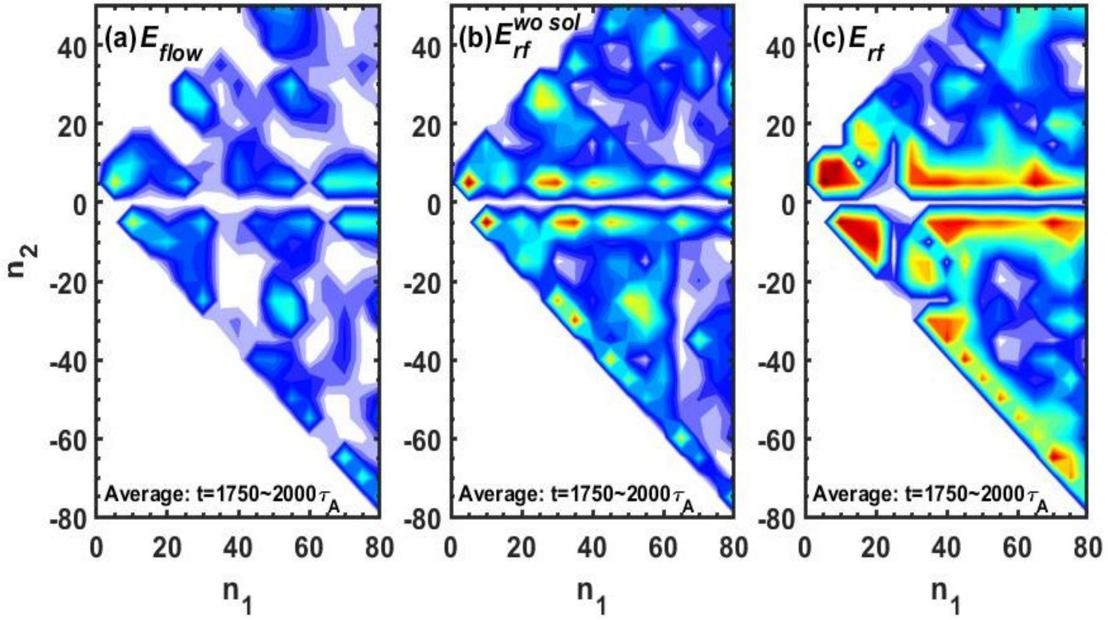
- Indirect effects by RF:
  - ☐ Pedestal scan for ELM
  - ☐ Edge turbulence & heat flux validations
- Direct effects by RF:
  - ☐ HCF effects on the turbulence & heat flux
  - ☐ RF sheath on ELM

ASIPP

The RF sheath by ICRF may suppress ELM effectively

- The RF sheath is able to suppress ELM from linear phase.
- The RF sheath generates the strong flow shear near the separatrix*, which leads to the widely nonlinear mode coupling.





more nonlinear modes coupling with the effects of the sheath potential

*B. Gui et al., NF 58 026027 (2018)

Summary

- The 6-field 2-fluid model in BOUT++ framework is developed to study the edge turbulence and ELMs for the typical RF heating H-mode on EAST
- The RF effects can be studied from 2 aspects:
- On equilibrium:
  - The pedestal scan shows the peak value of the divertor heat flux by ELM is proportional to $n_{e0\_SEP}\, T_{e0\_SEP}^{3/2}$
  - The mode coupling process generates the edge coherent mode. This mode can mitigate ELM.
- On instabilities:
  - HCF by LHW is able to mitigate the edge instabilities and broaden the SOL width
  - RF sheath by ICRF is able to suppress ELMs

More integrated simulations are necessary!

Thank you for your support!