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

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Various effective ELM control methods on EAST

- 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.

- 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)]
The effects of RF waves on edge instabilities

- **Indirect effects:**
  - Heating: profiles
  - Current driving: magnetic shear
  - Ponderomotive force: rotation
  - …

- **Direct effects:**
  - Current driving: topology
  - RF sheath: SOL rotation
  - Source terms
  - …

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


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

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

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

\[ q_{\parallel e} = 0.235 n_{e0,\text{SEP}} T_{e0,\text{SEP}}^{3/2} \]

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

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

\[ \kappa_{\text{eff,} j} = \frac{\kappa_{\parallel j} \kappa_{\text{fs,} j}}{\kappa_{\parallel j} + \kappa_{\text{fs,} j}} \]

\[ \kappa_{\text{fs,} j} = n_j v_{\text{th,} j} q R_0 \]
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Validations on coherent mode:

- Similar calculation of $f$ and $k$
- Simulated frequency is close to exp.
- $k_{\theta}$ 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.


EAST diagnostic
The simulated poloidal mode structures qualitatively agree with ECEI diagnostic.

- 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:
\[ S(n_1, n_2) = Y^*(n_3)Y(n_1)Y(n_2), \quad n_3 = n_1 + n_2. \]

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

\[ \frac{\partial \varphi(k,t)}{\partial t} = \Lambda_k \varphi(k,t) + \sum_{k_1 \geq k_2, k_1 + k_2 = k} \Lambda^Q_k(k_1, k_2) \varphi(k_1,t) \varphi(k_2,t) \]

Energy transfer rate*:
\[ \frac{\partial P_k}{\partial t} \approx \gamma_k P_k + T_k, \quad P_k = <\varphi_k \varphi_k^*>. \]

- **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)

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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.
  \[
  \tilde{P}_{PCM}(x,y,z,A) = Af(z) \cdot e^{\frac{(x-x_p)^2}{2\sigma_x^2} + \frac{(y-y_p)^2}{2\sigma_y^2}}.
  \]
  \[
  f(z) = [F(n,\theta)]_{FFT}.
  \]
  \[
  \tilde{P}_{PCM}(x,y,z,A) = A \cdot e^{\frac{(x-x_p)^2}{2\sigma_x^2} + \frac{(y-y_p)^2}{2\sigma_y^2}} [P_kz(n)e^{-i\theta}]_{FFT}.
  \]

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

- 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 $\lambda_q$ is indeed broadened by HCFs
- The splitting of strike point behavior is reproduced


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
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.
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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.

raised more nonlinear modes coupling with the effects of the sheath potential

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