The simulations on the control of ELM and edge turbulence by RF waves in EAST H-mode discharges

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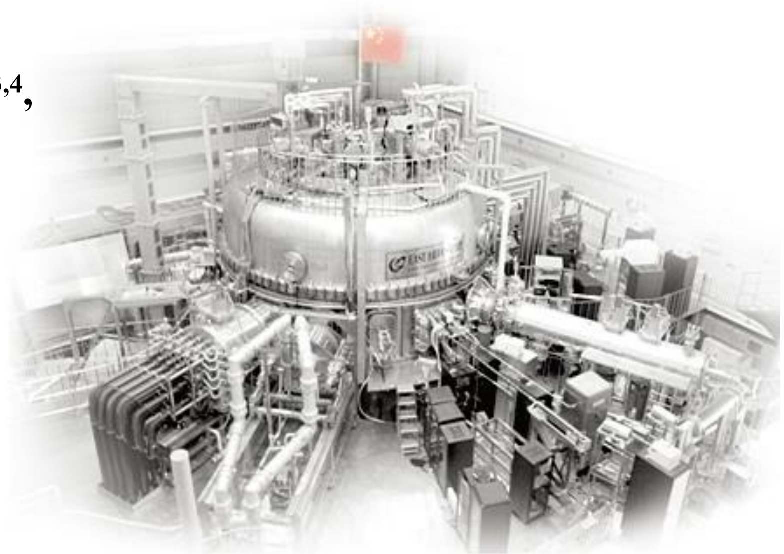

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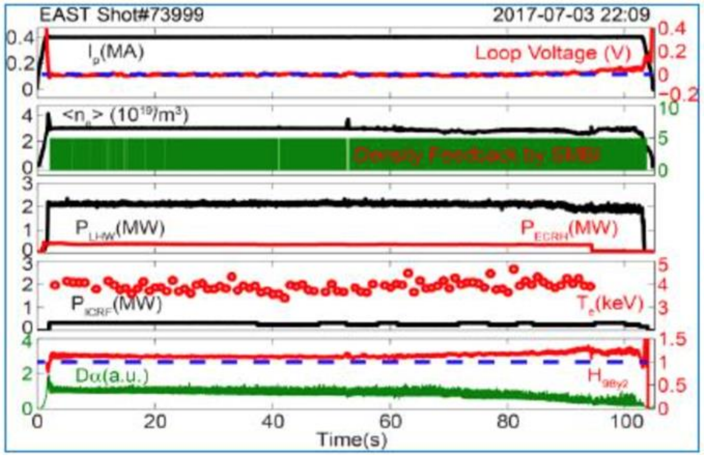
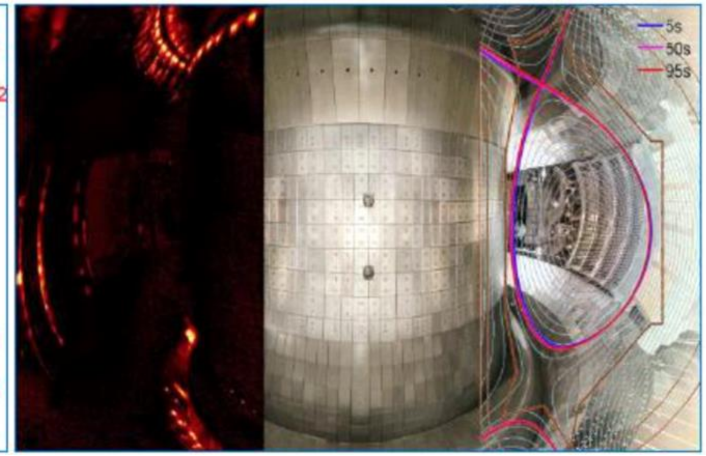
Outline

- **Motivations**
- **ELM mitigation by LHWs:**
  - **Helical current filaments**
  - **Pedestal coherent mode**
- **ELM suppression by RF sheath**
- **summary**

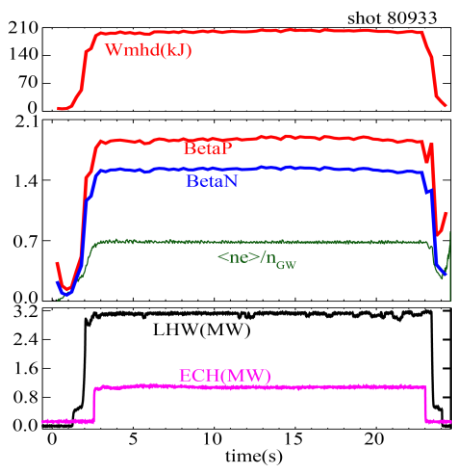
EAST aims at high performance & long pulse operation, The RF waves are necessary for the current drive & heating

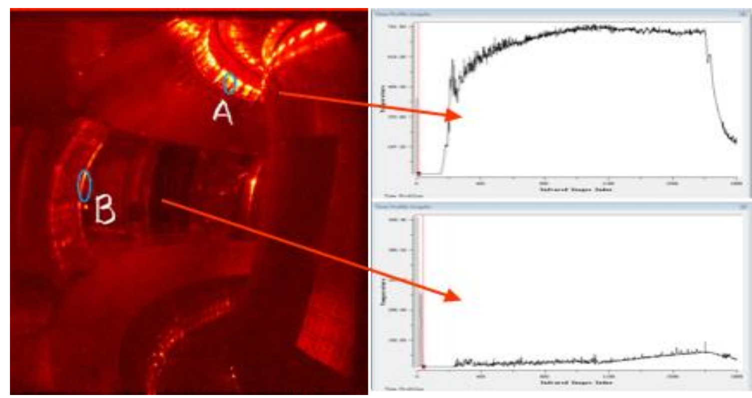
Long Pulse ~100s





High β_p





- **Challenge:**
  - **Avoidance of large ELMs**
  - **Low peak heat load/Tolerable transient heat shock**

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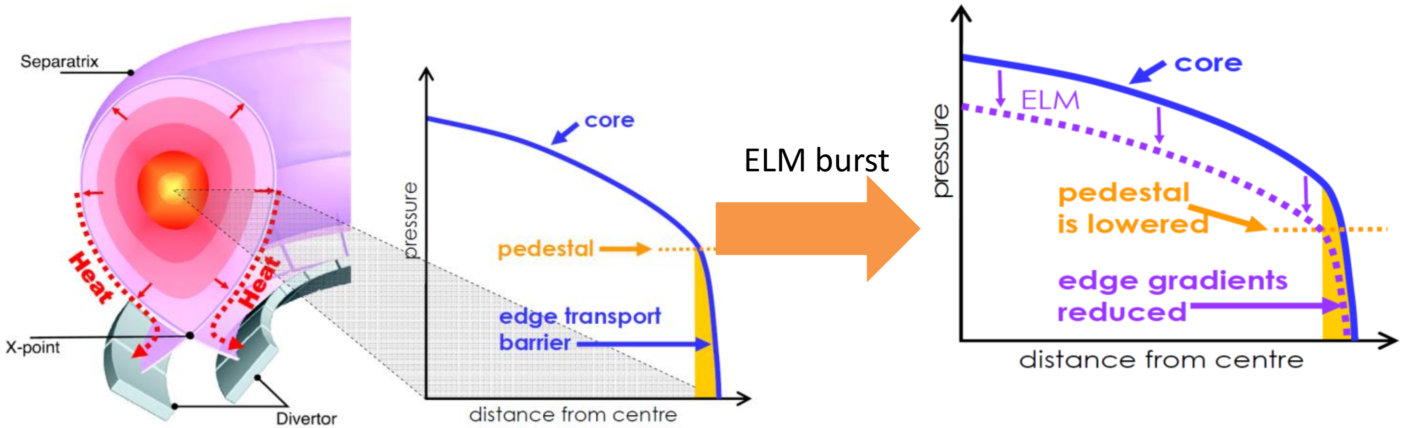
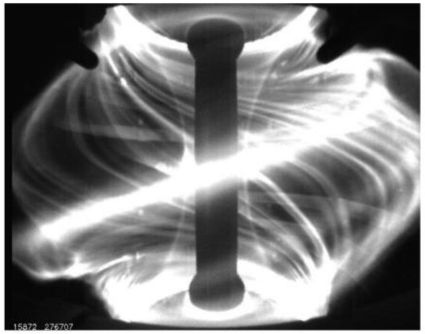
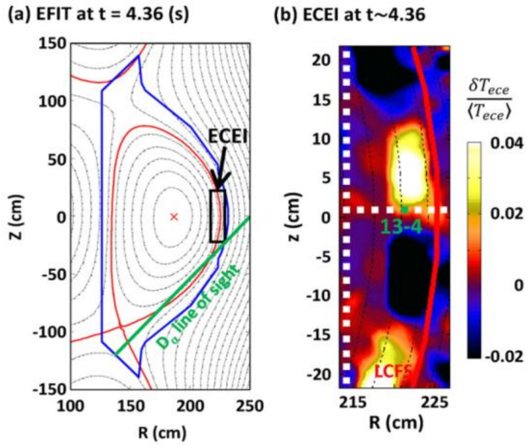
The transient heat flux by Edge localized mode (ELM) is one of the main issue for the steady-state operation

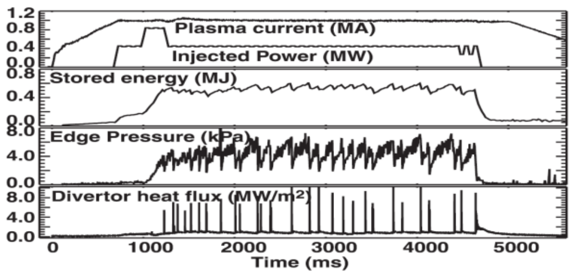




High speed video image in visible light of the MAST plasma obtained at the start of an ELM



ELM filaments by ECEI on KSTAR



A typical type-I ELM on DIII-D
(A. Leonard, PoP 21, 090501 (2014))

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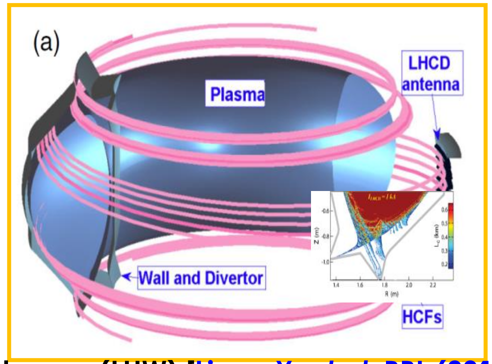
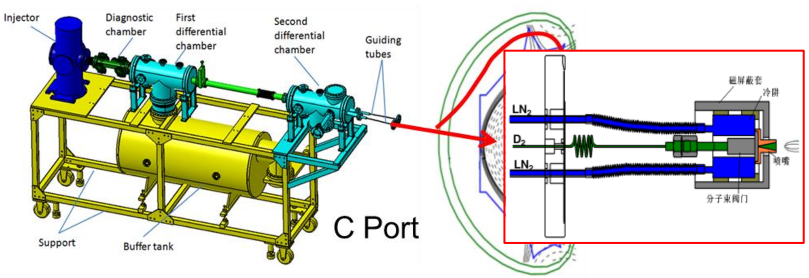
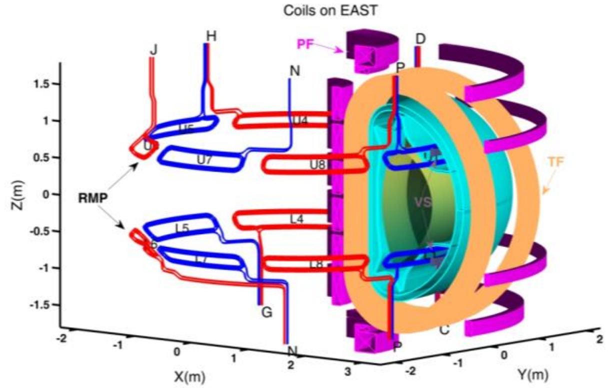
RF wave is one of the effective ELM control method on EAST



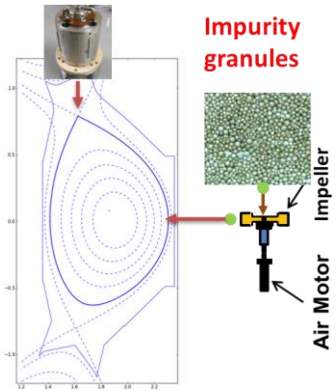
Lower Hybrid wave (LHW) [Liang Y. *et al*, PRL (2013)]



Pellet, super-sonic molecular beam injection (SMBI)



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



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

- EAST is specific on the operation under the ITER-like long-pulse, low rotation and metal wall conditions.
- Various ways of ELM control have been developed on EAST successfully.

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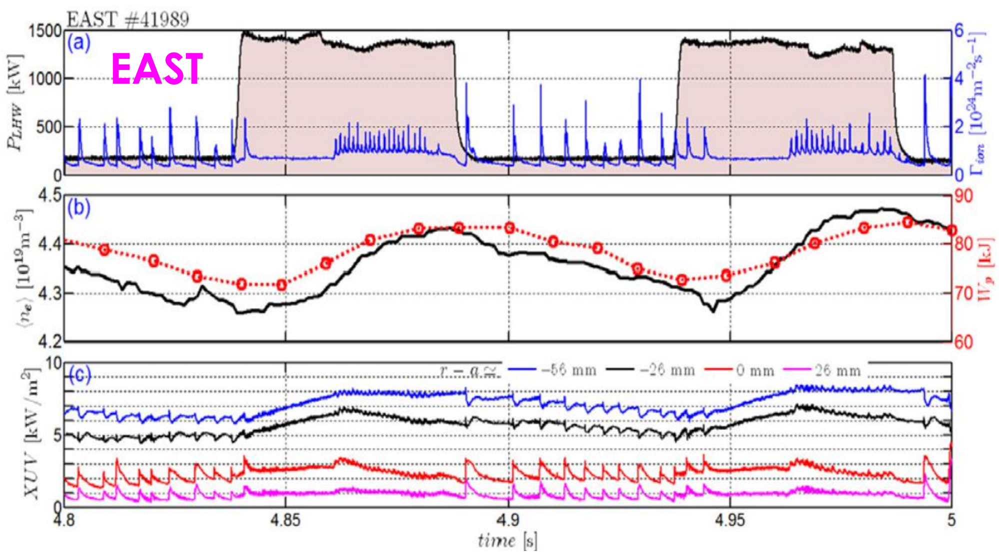
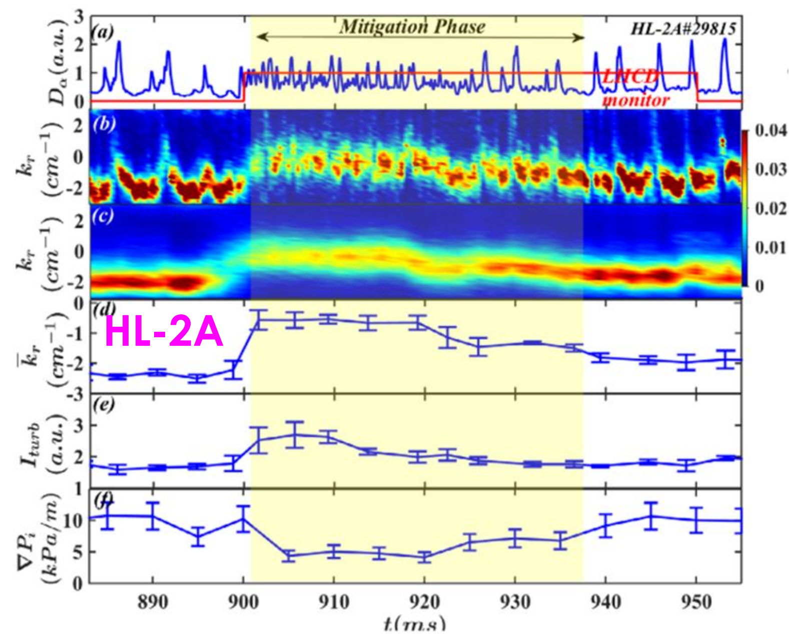
Lower-hybrid waves show suppression effects on ELMs in EAST & HL-2A

LHWs suppress & mitigate ELMs



R. Chen, et al., Nucl. Fusion 55 (2015) 033012



G.L. Xiao, et al., Nucl. Fusion 59 (2019) 126033

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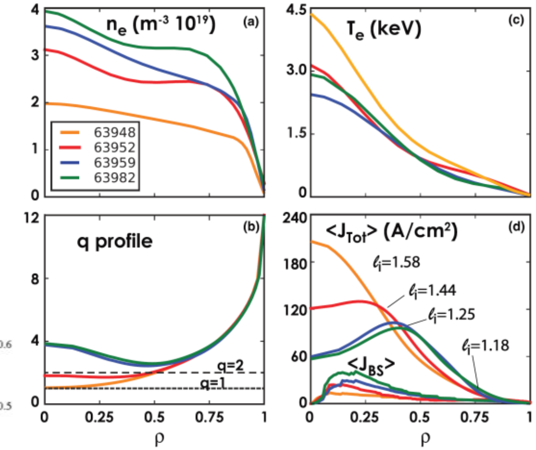
The effects of RF waves on edge instabilities

➢Indirect effects:

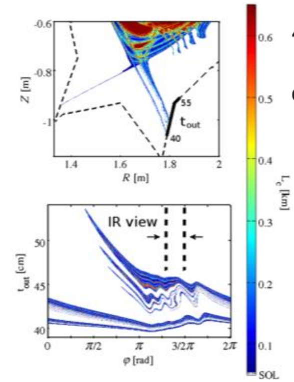
- ☐ Heating: change profiles
- ☐ Current driving: change magnetic shear
- ☐ Ponderomotive force: change rotation
- ☐ …

➢Direct effects:

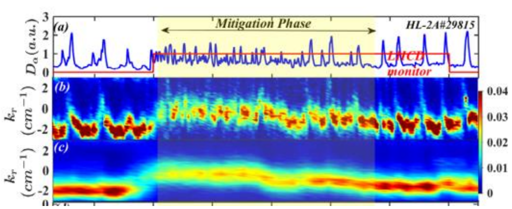
- ☐ Current driving: change topology
- ☐ Turbulence enhancement
- ☐ RF sheath: change SOL rotation
- ☐ Source terms
- ☐ …



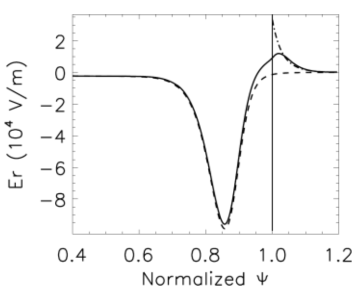
A. Garrofallo et al., NF 57 076037 (2017)



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



G.L. Xiao, et al., Nucl. Fusion 59 (2019) 126033



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

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

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

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

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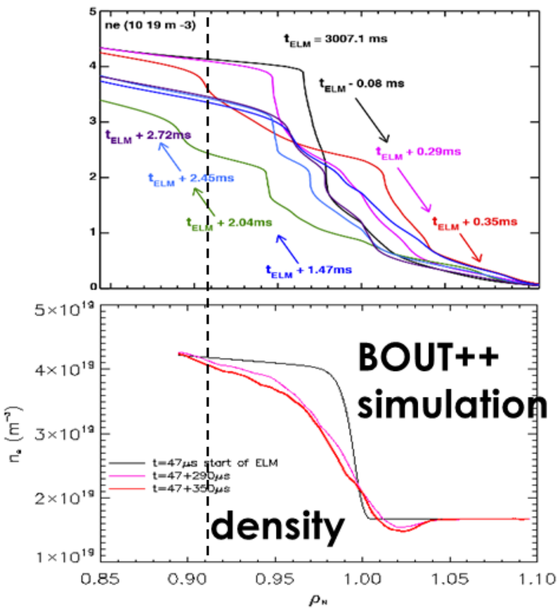
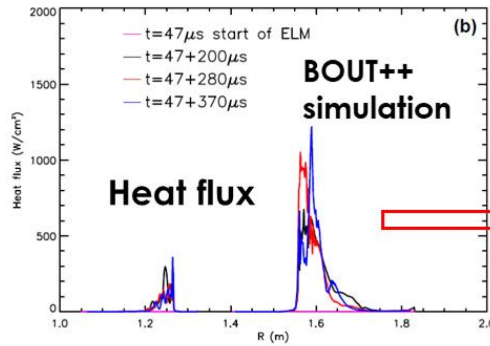
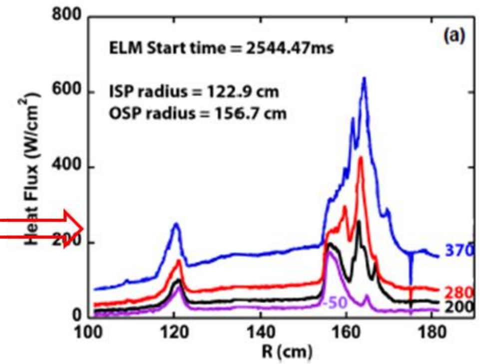
BOUT++ framework has been used to reproduce the profile change & transient fluxes induced by edge instabilities

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



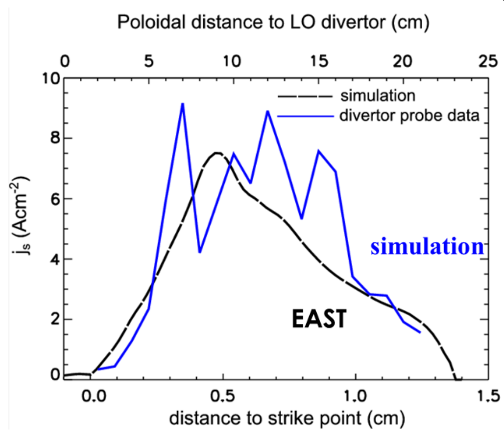
Density evolution during ELM on DIII-D





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

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- Motivations
- ELM mitigation by LHWs:
  - Helical current filaments
  - Pedestal coherent mode
- ELM suppression by RF sheath
- summary

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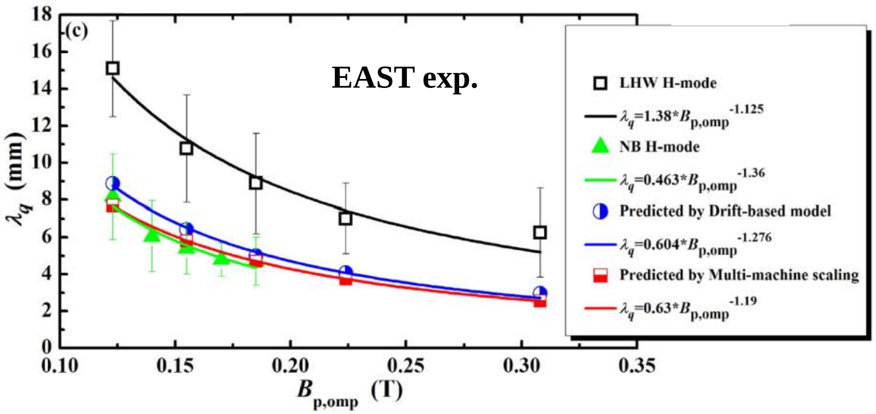
The helical current filaments (HCFs) by LHW are believed to broad the SOL width

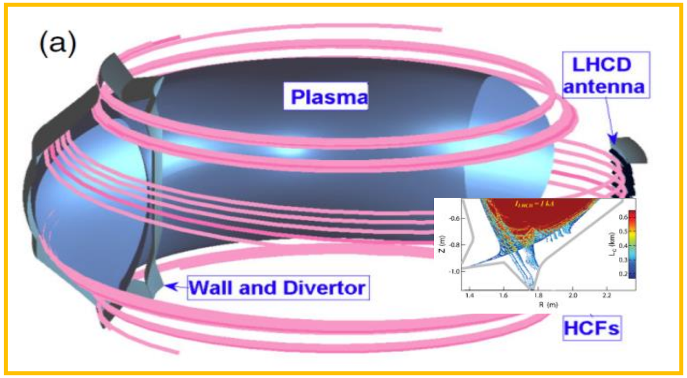


G.Z. Deng, et al., Plasma Phys. Control. Fusion 60 (2018) 045001

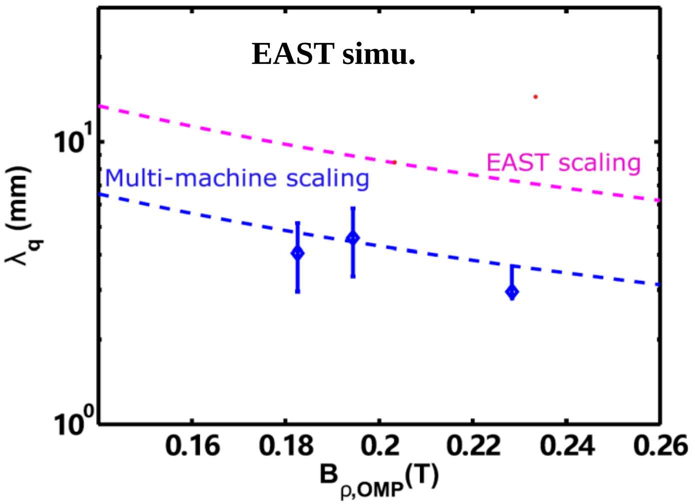
- The SOL width scaling on EAST is larger than the multi-machine scaling

$$\lambda_q = (0.63 \pm 0.08) \times B_{\mathrm{p,omp}}^{-(1.19 \pm 0.08)}$$

- Radio-frequency heating leads to the difference
- LHW induces HCFs, which can split the strike point



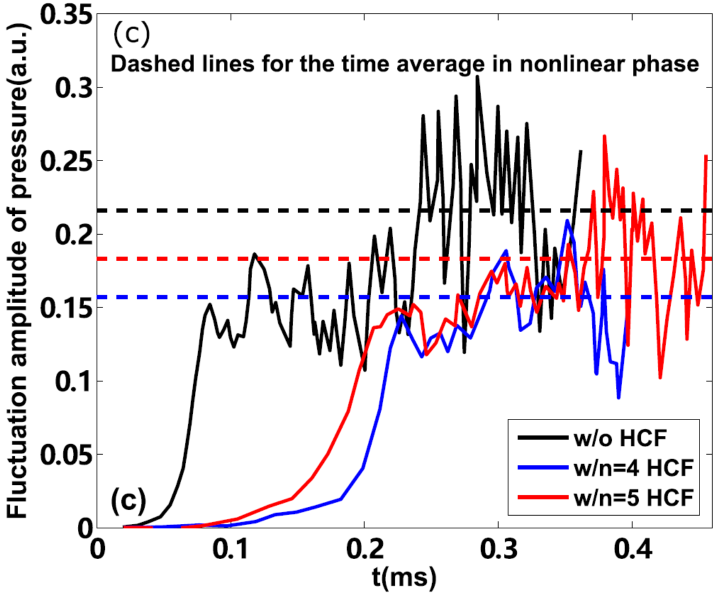
Y.F. Liang et al., PRL 110, 235002 (2013).

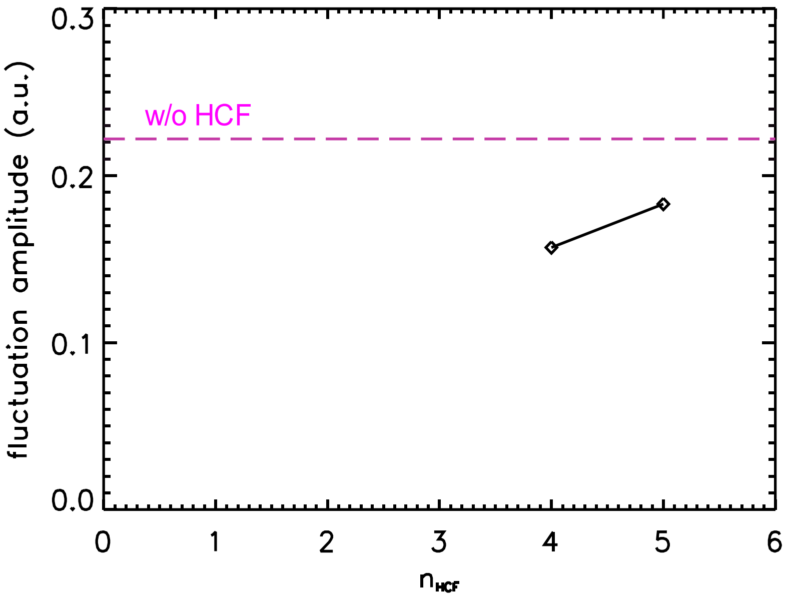


T.Y. Xia, et al., Nucl. Fusion 57 (2017) 116016

The BOUT++ simulations show HCF is also able to mitigate edge fluctuations

- ➢ 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





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

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

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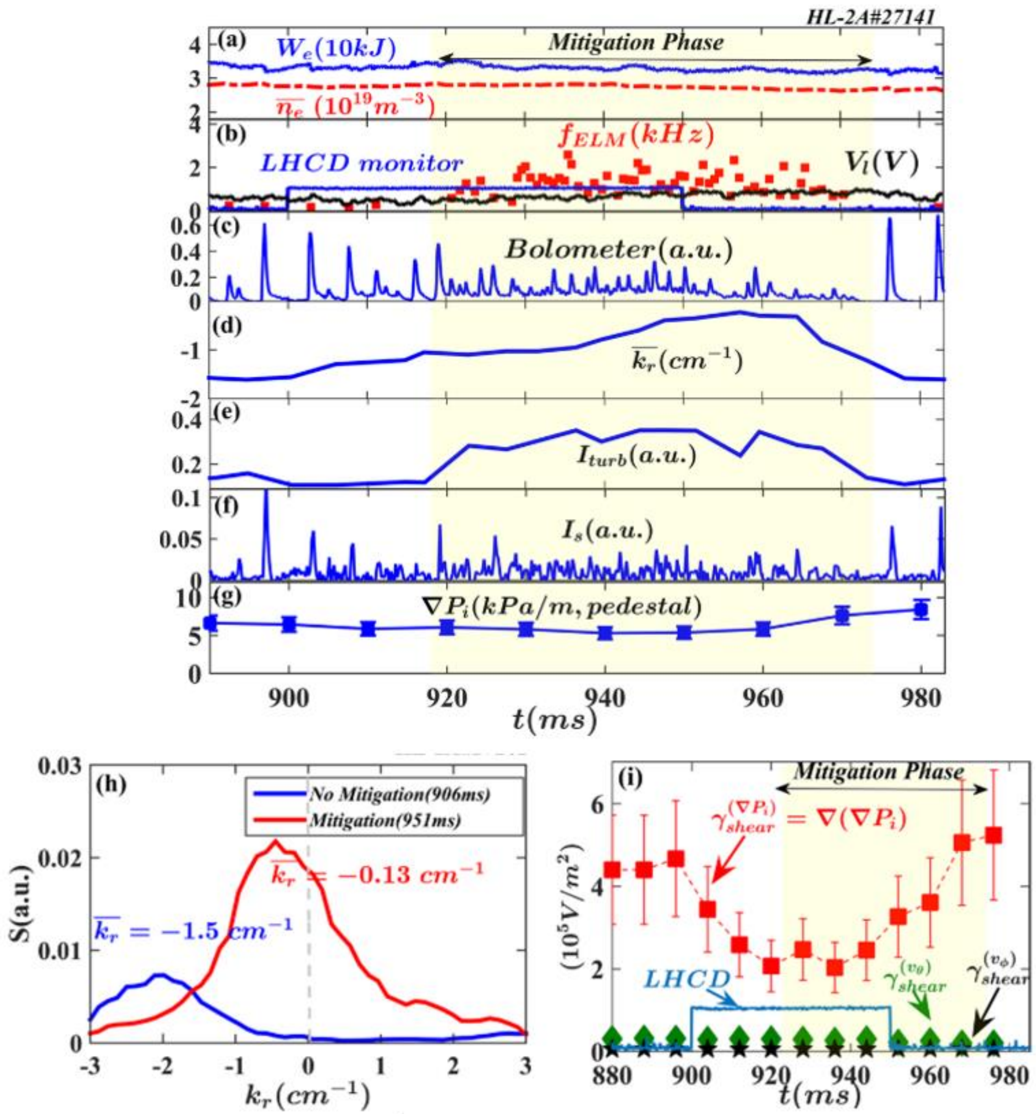
Turbulence enhancement is found to be effective for ELM mitigation



LHW modified the pedestal ion pressure gradient

↓

A reduction of the ion diamagnetic term of the edge E×B velocity shear

↓

The kr of the pedestal turbulence shifted

↓

The pedestal turbulence is enhanced

↓

ELM mitigation

G.L. Xiao, et al., Nucl. Fusion 59 (2019) 126033

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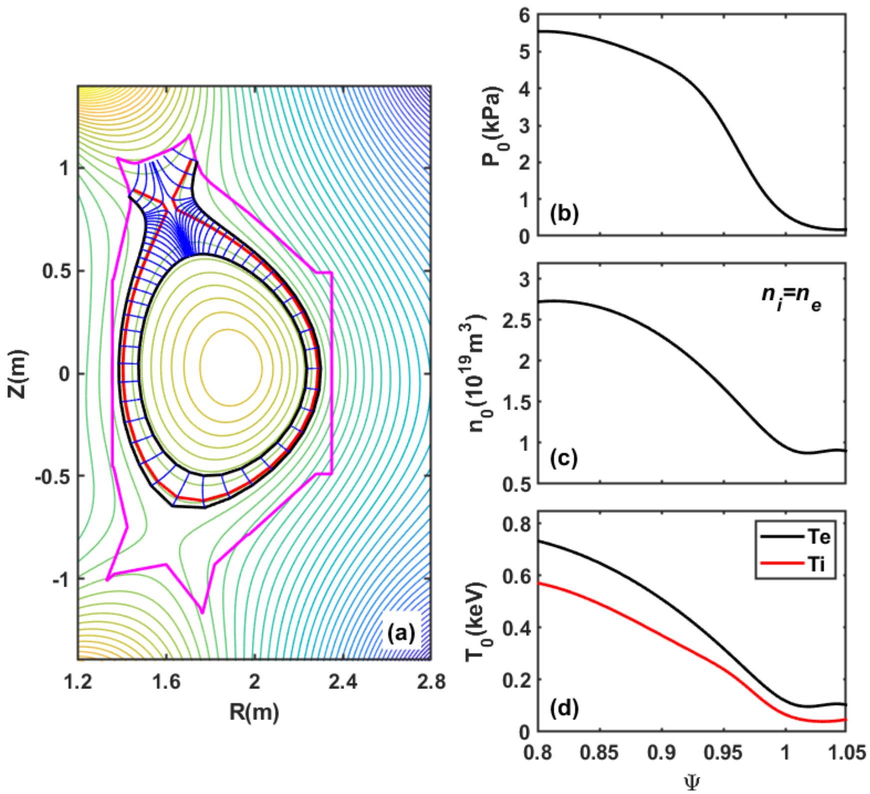
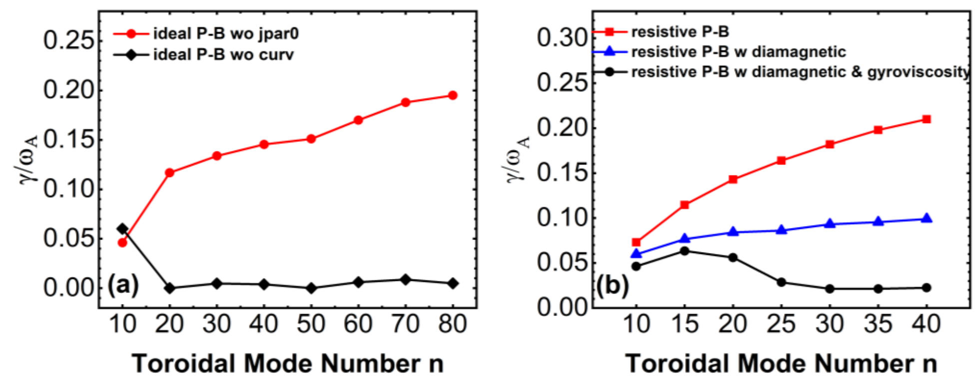
An EAST ELMy H-mode discharge is used for the simulations

Simulation domains & profiles: EAST#77741@5.1s





- **The equilibrium is ideal ballooning unstable**
- **RBM is unstable, but not important**
- **FLR stabilizes the high n mode**

- **Equilibrium is reconstructed by k-EFIT**
- **Simulation domain includes pedestal & SOL**

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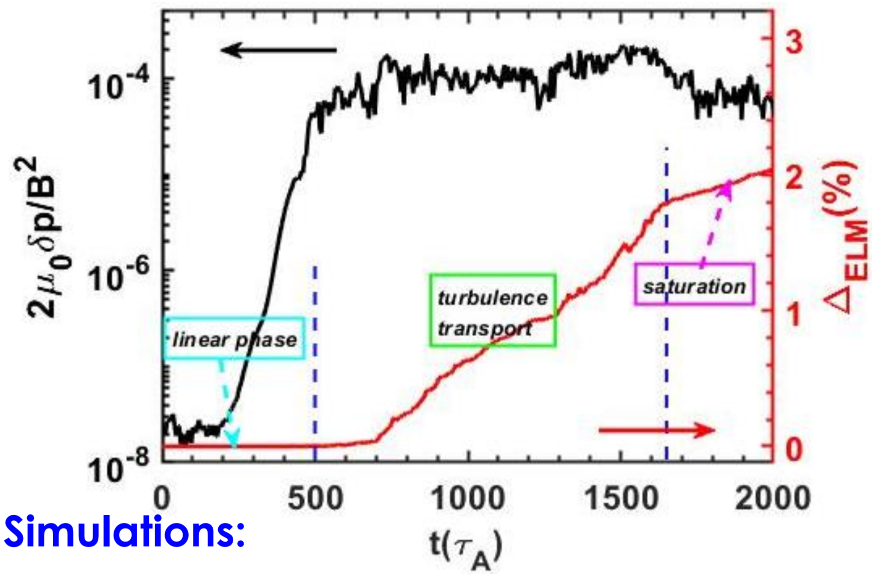
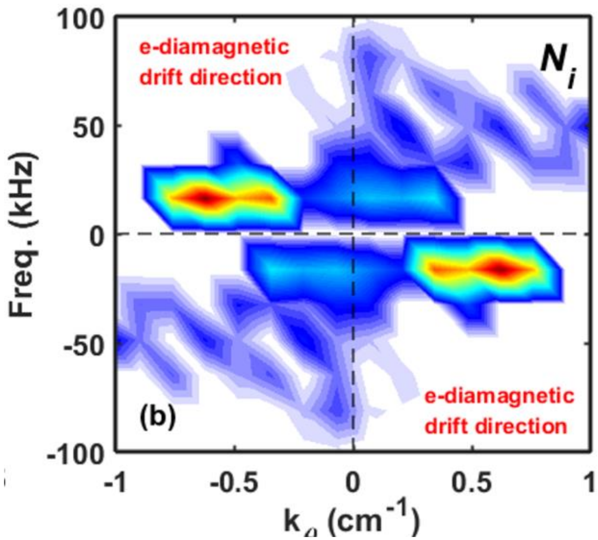
The direct simulations obtains a large ELM & QCM



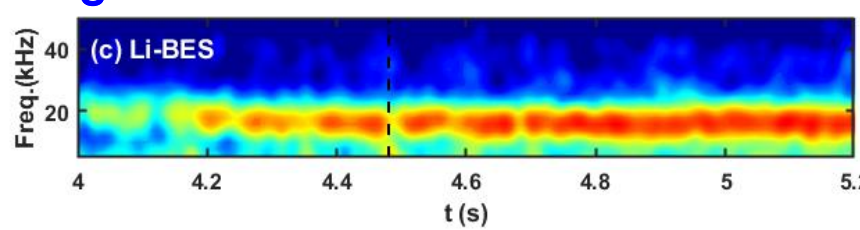
Simulations:



Nonlinear simulations:

- ELM size **>2%**, large ELM
- Saturated fluctuation amplitude: **~10^{-4}**
- A QCM is found after ELM crash, on e-diamagnetic direction
- f_{QCM}**~20kHz**, similar to the Li-BES diagnostic

Diagnostic:

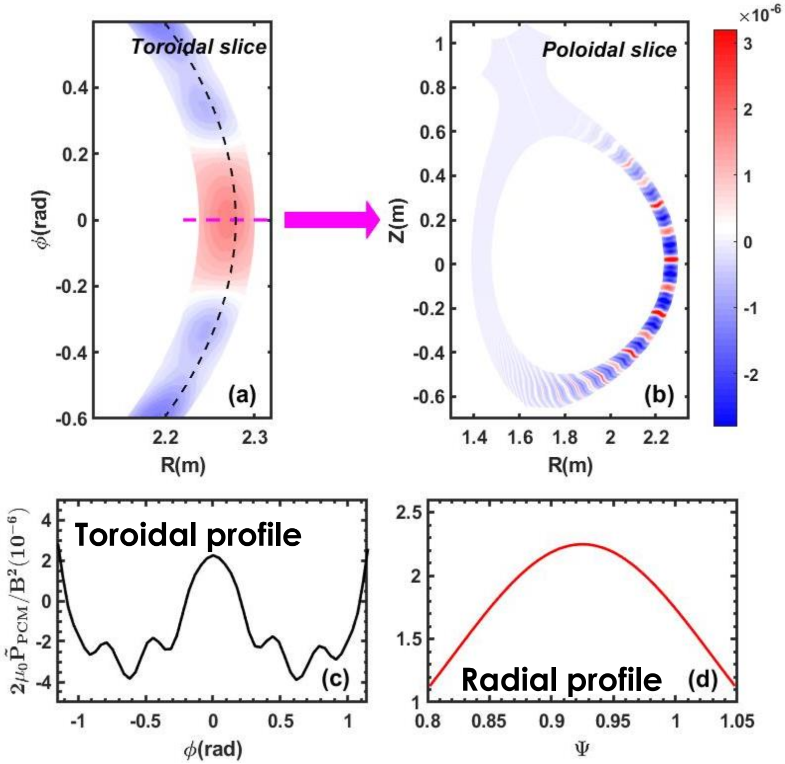


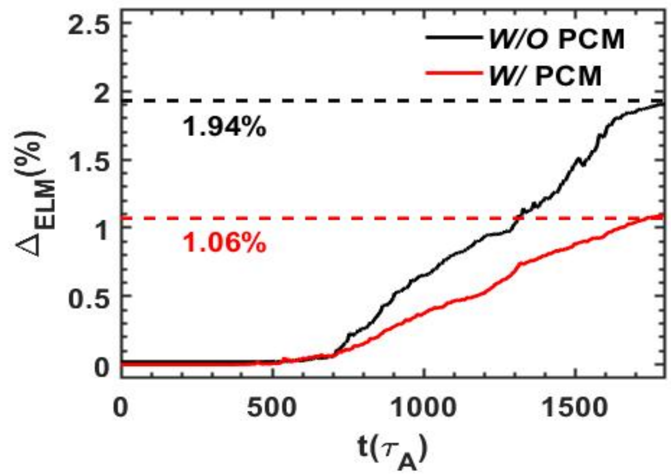
Focusing on the interaction between turbulence and ELM

A modelled PCM is able to decrease ELM size

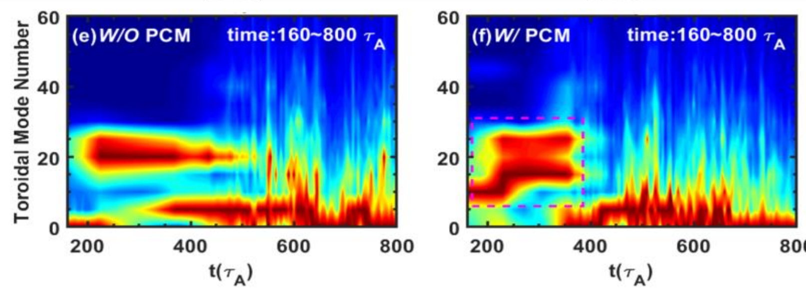
A modelled pedestal coherent mode is added into BOUT++ as the initial condition:

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





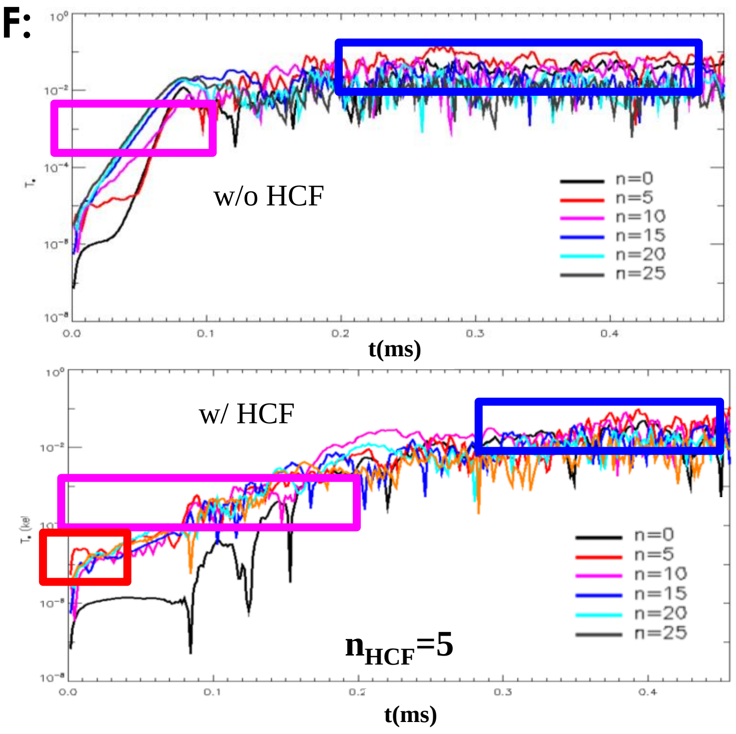
- For better scan of the key parameters,
- ELM size is decreased by **~45%**
- The dominant mode in linear phase is changed by PCM



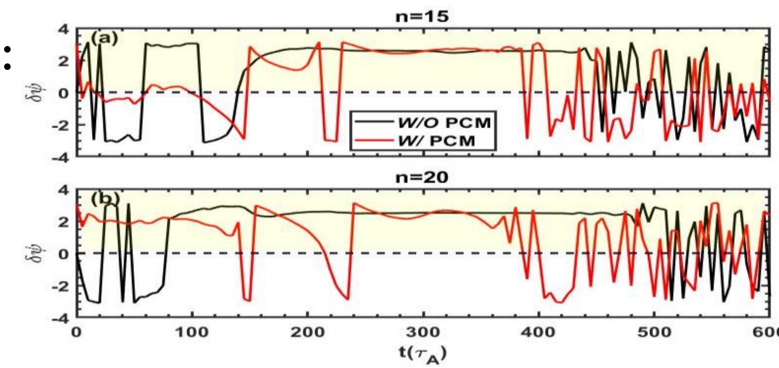
Mechanism: nonlinear interactions limit the saturation amplitude of ELM

- **Similar mechanism for HCF and PCM:**
  Nonlinear mode interactions among multi modes driven by HCF Br or PCM decrease the phase coherent time (P.W. Xi, PRL, 2014) and leads to the slow growing.
- **Difference:**
  intimal magnetic perturbation for HCF;
  initial electrostatic perturbation for PCM

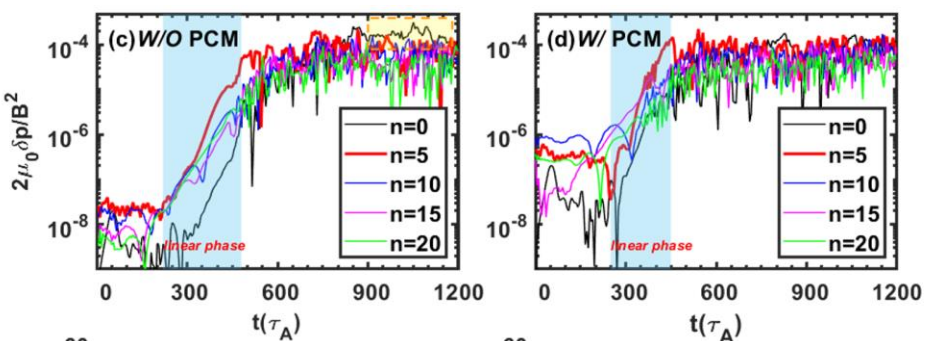
HCF:



PCM:



phase coherent time is shortened by PCM



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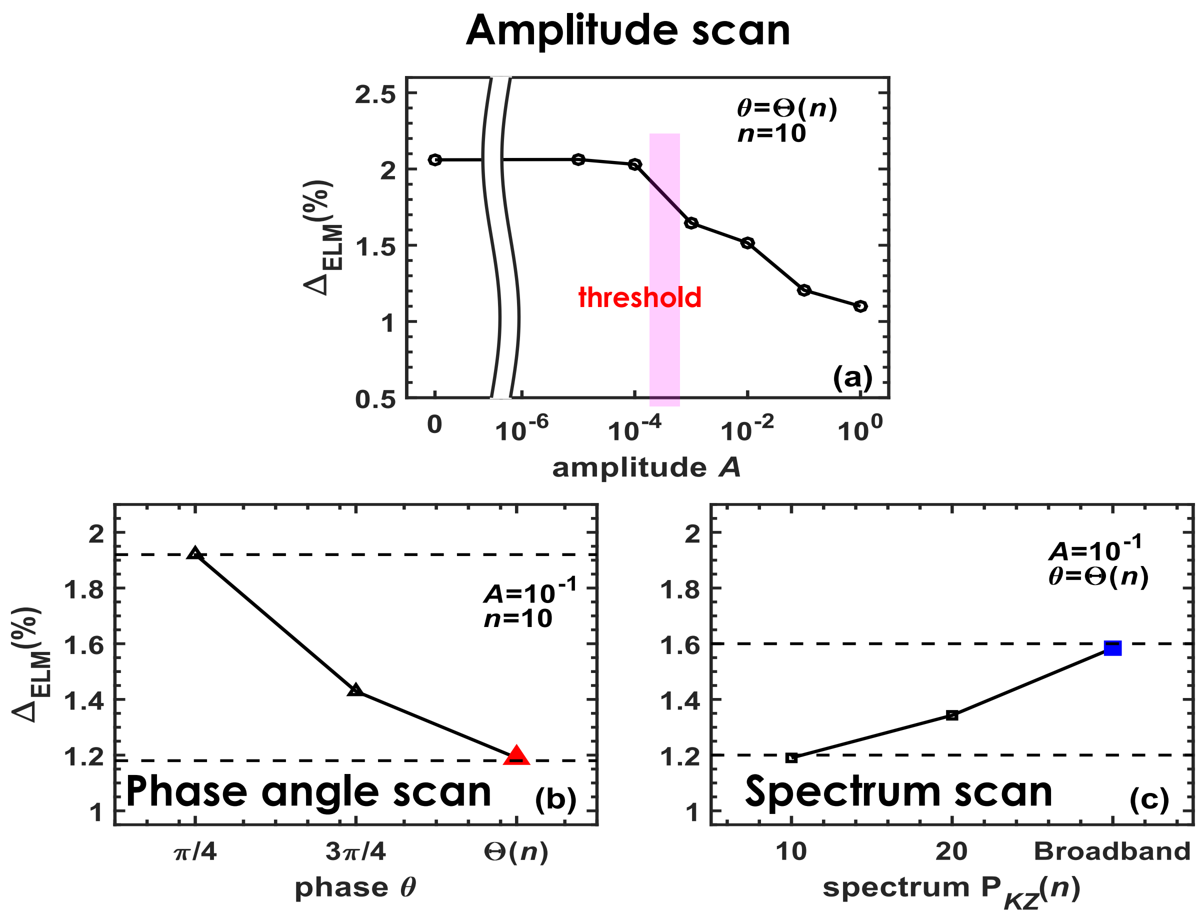
The key parameter scan show a threshold of PCM amplitude for ELM mitigation



- The ELM size trends to be smaller when the A becomes larger
- The phase angle reduces the ELM size by up to 37%
- Dominant PCM modes also affect the ELM size

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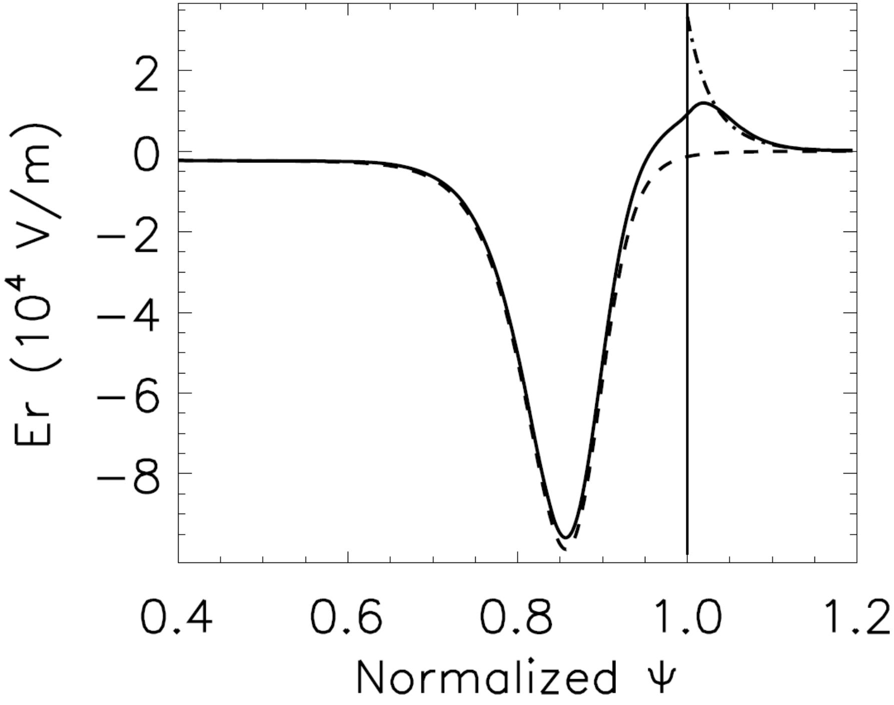
RF sheath potential module is developed to calculate the SOL radial electric field in tokamaks

The RF sheath located near the antenna region for RF heating scheme
A minimal 2-field model is developed in BOUT++ framework

$$\frac{\partial \varpi}{\partial t} = B_0 \nabla_\| J_\| + \mu_{i,\perp} \nabla_\perp^2 \varpi + \mu_{i,\|} \nabla_\|^2 \varpi$$

$$\varpi = \frac{n_0 M_i}{B_0} (\nabla_\perp^2 \phi + \frac{1}{n_0 Z_i e} \nabla_\perp^2 P_i)$$

$$J_\| = -\frac{1}{\eta} \nabla_\| \phi + \frac{1}{\eta e n_e} \nabla_\| P_e + \frac{0.71 k_B}{\eta e} \nabla_\| T_e.$$



- **A positive Er forms in SOL.**
- **Smoothly connected across the separatrix to the force-balanced Er in pedestal.**

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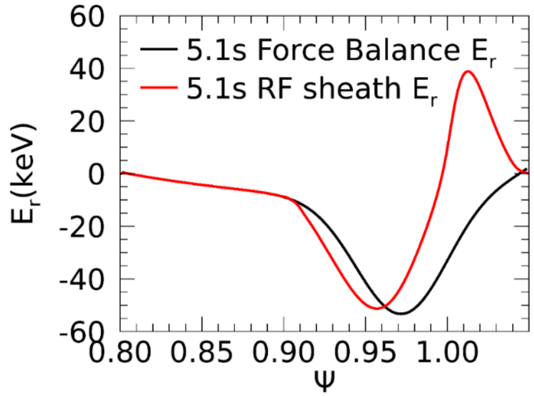
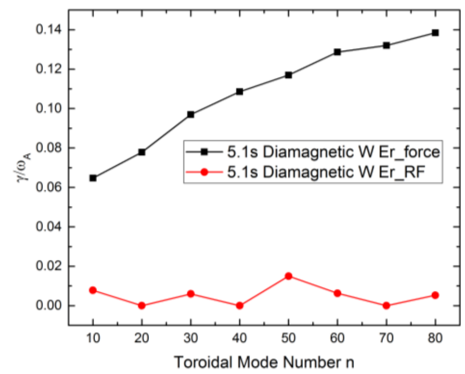
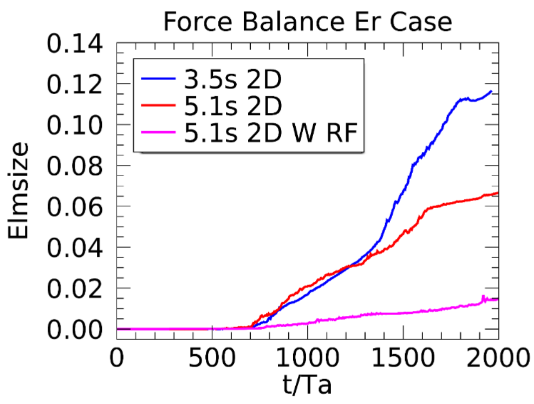
Gui B. et al Nucl. Fusion 58 (2018) 026027

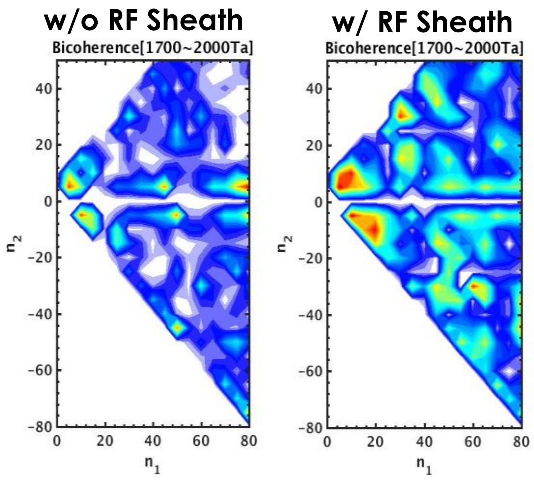
The large E_r shear by RF sheath potential suppresses ELM

- **Based on the same EAST ELMy H-mode equilibrium #77741**
- **Start from the same equilibrium, only E_r different**
- **The linear growth rates are decreased by E_r with RF sheath**
- **Simulated ELM sizes are effectively decreased by RF sheath from 3.6% to 0.4%**
- **Strong mode couplings are found w/ RF sheath**









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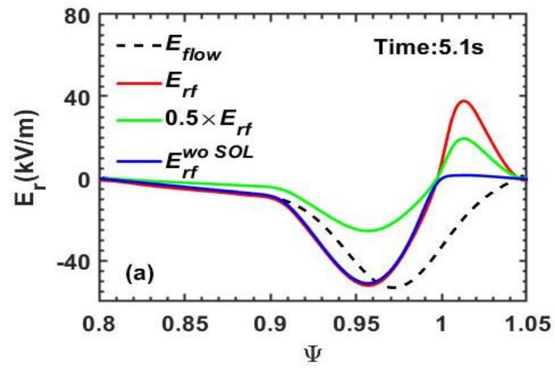
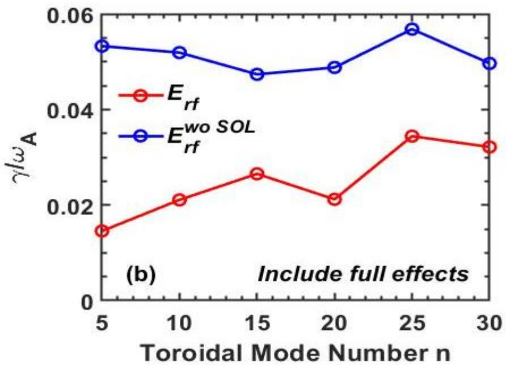
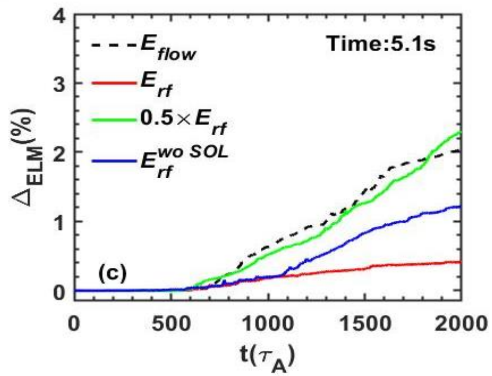
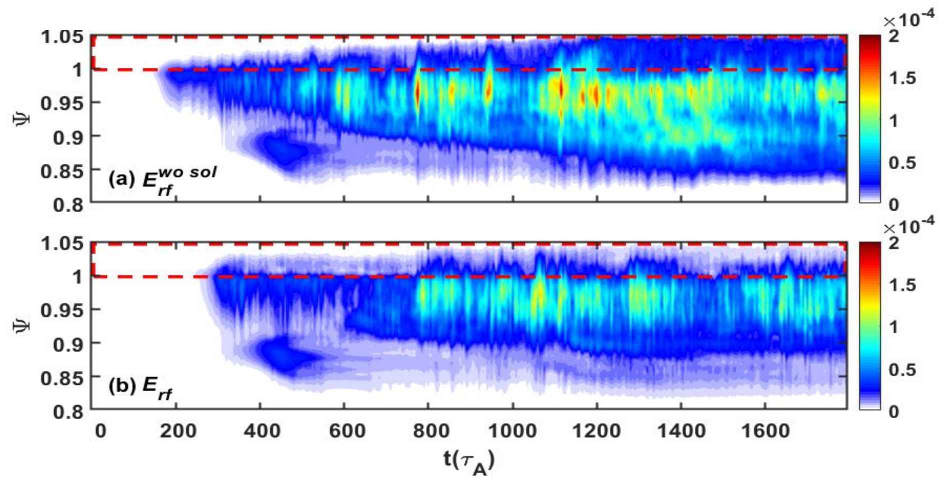
The Er shear in SOL region is important for the ELM suppression





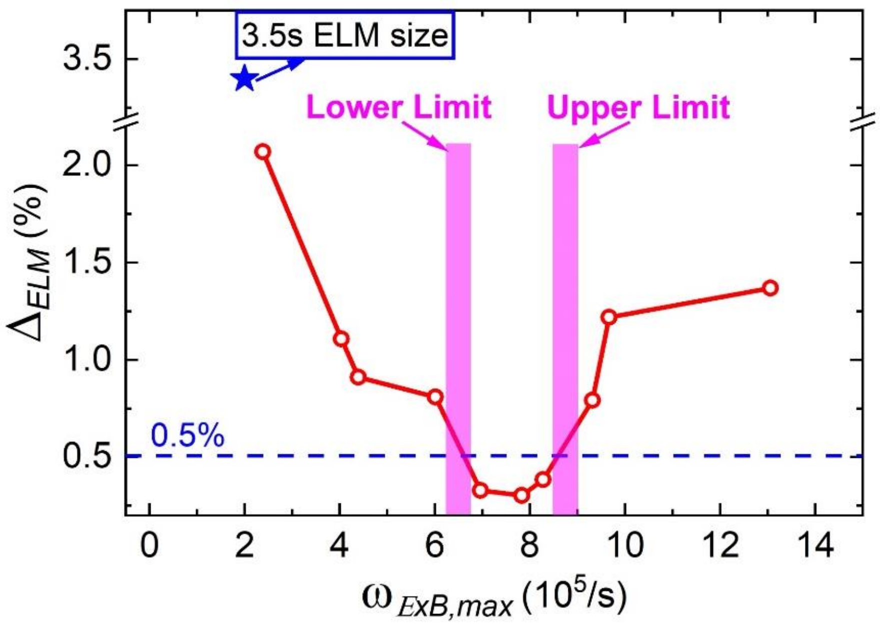


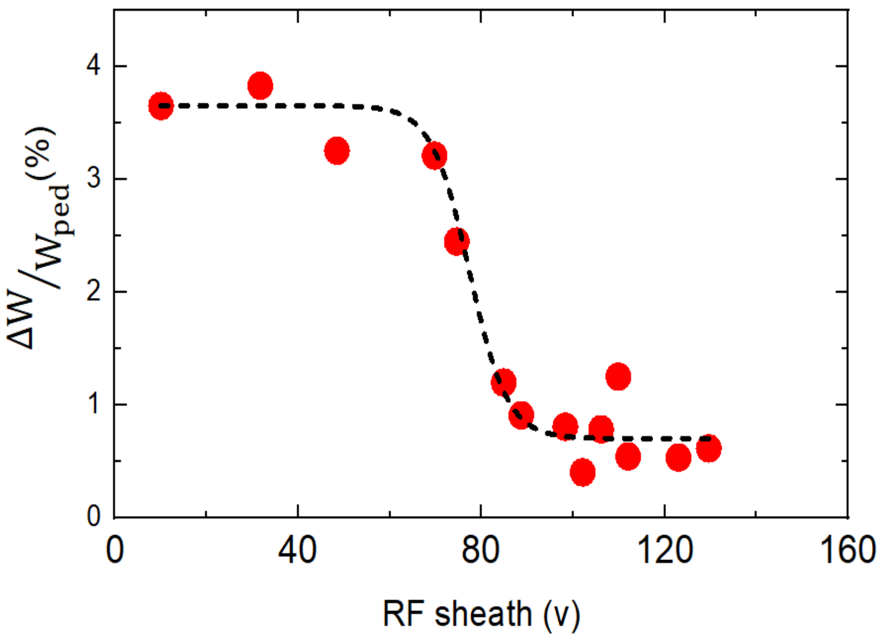
- A modelled Er, same in pedestal but w/o shear in SOL, is tested
- Linear grwothrate is increased w/o SOL shear
- ELM size is also increased
- Half of the RF Er loses the suppression effects



- The mode expansion on radial direction is limited by Er shear

A narrow window is found to suppress ELM by RF Er shear





- Only a small window of the shear can suppress ELM effectively
- High requirement on the RF sheath potential
- Not easy to be found on experiments

ASIPP

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 3 aspects:

  - ✓ HCF by LHW is able to mitigate ELMs through the nonlinear interactions.
  - ✓ PCM enhanced by LHW can mitigate ELM by reducing the phase coherent time
  - ✓ RF sheath by RF antenna is capable to suppress ELMs by decreasing linear growthrates.

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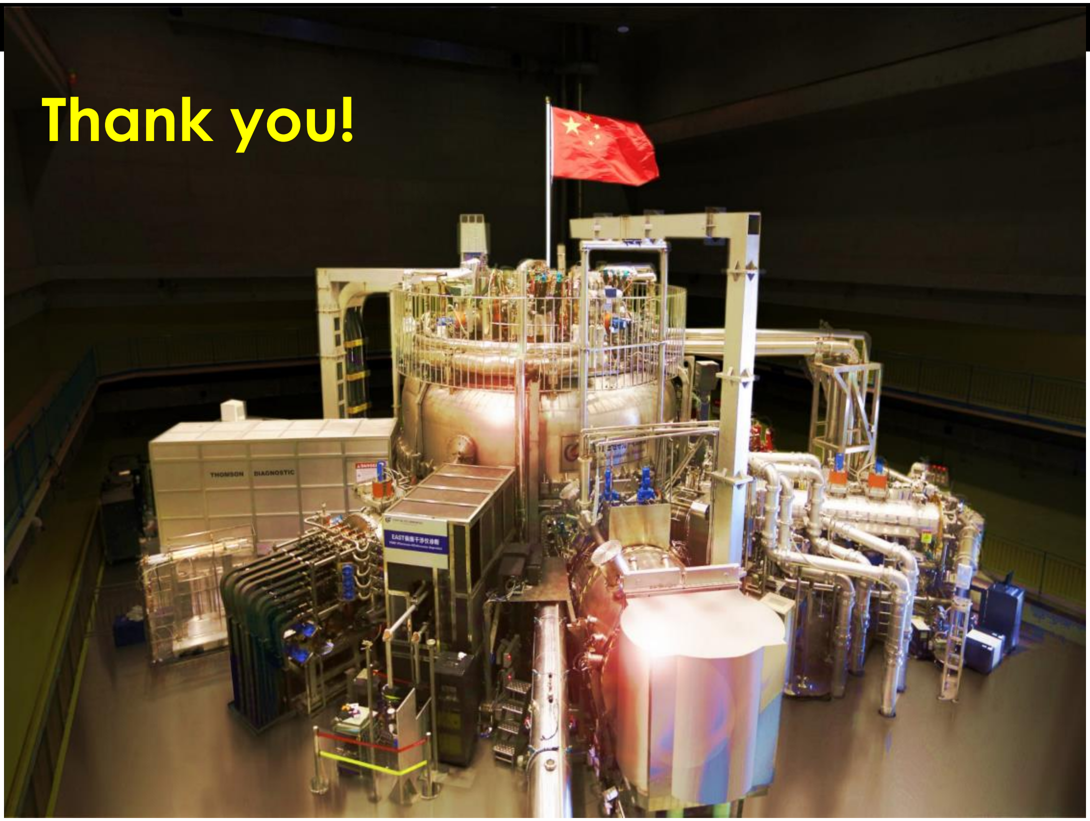
Thank you!
THOMSON DIAGNOSTIC

6-field 2-fluid module in BOUT++ is developed for the turbulence and transient heat flux study

$$
\begin{aligned}
\frac{\partial}{\partial t}\varpi &= -\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\Phi\cdot\boldsymbol{\nabla}\varpi + B_0^2\nabla_\parallel\left(\frac{J_\parallel}{B_0}\right) + 2\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\boldsymbol{\nabla}p_i \\
&\quad -\frac{1}{2\Omega_i}\left[\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}P_i\cdot\boldsymbol{\nabla}\left(\nabla_\perp^2\Phi\right) - Z_i e B_0\boldsymbol{b}\times\boldsymbol{\nabla}n_i\cdot\boldsymbol{\nabla}\left(\frac{\nabla_\perp\Phi}{B_0}\right)^2\right] \\
&\quad +\frac{1}{2\Omega_i}\left[\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}\Phi\cdot\boldsymbol{\nabla}\left(\nabla_\perp^2 P_i\right) - \nabla_\perp^2\left(\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}\Phi\cdot\boldsymbol{\nabla}P_i\right)\right] + \mu_{\parallel i}\nabla_{\parallel 0}^2\varpi, \qquad (1) \\
\frac{\partial}{\partial t}n_i &= -\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\Phi\cdot\nabla n_i - \frac{2n_i}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\boldsymbol{\nabla}\Phi \\
&\quad -\frac{2}{Z_i e B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\boldsymbol{\nabla}P_i - n_i B_0\nabla_\parallel\left(\frac{V_{\parallel i}}{B_0}\right), \qquad (2) \\
\frac{\partial}{\partial t}V_{\parallel i} &= -\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\Phi\cdot\boldsymbol{\nabla}V_{\parallel i} - \frac{1}{m_i n_{i0}}\boldsymbol{b}\cdot\boldsymbol{\nabla}P, \qquad (3) \\
\frac{\partial}{\partial t}A_\parallel &= -\nabla_\parallel\phi + \frac{\eta}{\mu_0}\nabla_\perp^2 A_\parallel + \frac{1}{e n_{e0}B_0}\nabla_\parallel P_e + \frac{0.71 k_B}{e B_0}\nabla_\parallel T_e - \frac{\eta_H}{\mu_0}\nabla_\perp^4 A_\parallel, \qquad (4) \\
\frac{\partial}{\partial t}T_i &= -\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\Phi\cdot\boldsymbol{\nabla}T_i \\
&\quad -\frac{2}{3}T_i\left[\left(\frac{2}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\right)\cdot\left(\boldsymbol{\nabla}\Phi + \frac{1}{Z_i e n_{i0}}\boldsymbol{\nabla}P_i + \frac{5}{2}\frac{k_B}{Z_i e}\boldsymbol{\nabla}T_i\right) + B_0\nabla_\parallel\left(\frac{V_{\parallel i}}{B_0}\right)\right] \\
&\quad +\frac{2}{3n_{i0}k_B}\nabla_{\parallel 0}\left(\kappa_{\parallel i}\nabla_{\parallel 0}T_i\right) + \frac{2}{3n_{i0}k_B}\boldsymbol{\nabla}_\perp\cdot\left(\kappa_{\perp i}\boldsymbol{\nabla}_\perp T_i\right) + \frac{2m_e}{m_i}\frac{Z_i}{\tau_e}\left(T_e - T_i\right) \qquad (5) \\
\frac{\partial}{\partial t}T_e &= -\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\Phi\cdot\boldsymbol{\nabla}T_e \\
&\quad -\frac{2}{3}T_e\left[\left(\frac{2}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\right)\cdot\left(\boldsymbol{\nabla}\Phi - \frac{1}{e n_{e0}}\boldsymbol{\nabla}P_e - \frac{5}{2}\frac{k_B}{e}\boldsymbol{\nabla}T_e\right) + B_0\nabla_\parallel\left(\frac{V_{\parallel e}}{B_0}\right)\right] \\
&\quad +0.71\frac{2T_e}{3e n_{e0}}B_0\nabla_\parallel\left(\frac{J_\parallel}{B_0}\right) + \frac{2}{3n_{e0}k_B}\nabla_{\parallel 0}\left(\kappa_{\parallel e}\nabla_{\parallel 0}T_e\right) + \frac{2}{3n_{e0}k_B}\boldsymbol{\nabla}_\perp\cdot\left(\kappa_{\perp e}\boldsymbol{\nabla}_\perp T_e\right) \\
&\quad -\frac{2m_e}{m_i}\frac{1}{\tau_e}\left(T_e - T_i\right) + \frac{2}{3n_{e0}k_B}\eta_\parallel J_\parallel^2 \qquad (6)
\end{aligned}
$$

Compressible terms

Parallel velocity terms

Electron Hall

Thermal force

Gyro-viscosity

Energy exchange

Energy flux

Thermal conduction

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