中国科学院等离子体物理研究所

Institute of Plasma Physics Chinese Academy of Sciences

——2023 BOUT++ Workshop, Livermore, California, USA

The simulation of ELMs suppression by ion cyclotron resonance heating in EAST using BOUT++

Yanlong Li[1], Tianyang Xia[1], Minyou Ye[2], Xiaolan Zou[3], Xinjun Zhang[1], Chu Zhou[2], Shifeng Mao[2], Bin Gui[1], Guanghai Hu[1], and EAST team[1]

[1]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, People's Republic of China*

[2]*University of Science and Technology of China, Hefei, People's Republic of China*

[3]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

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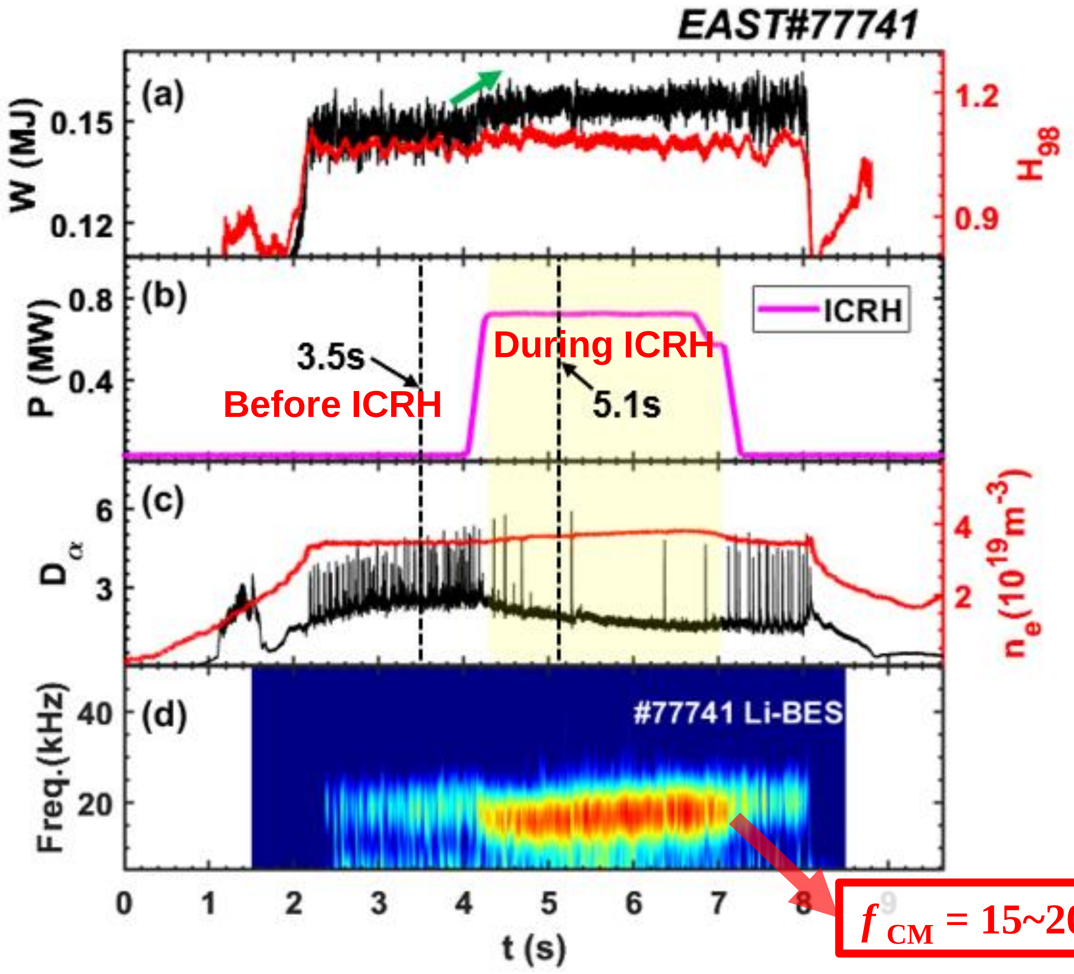
Outline

- **Experimental background**
- **Simulation results**
  - **Effect of pedestal structure on ELM**
  - **Effect of RF sheath on ELM**
- **Summary**

First observation of ELM suppression by ICRH in EAST

In June 2018, the phenomenon that ELMs are completely suppressed by ICRH during H mode, was first observed in EAST[1]. However, due to the complexity of the experimental environment, the mechanism of ELM suppression by ICRH is still not very clear.



f_{CM} = 15~20 kHz

➢ Experiment:

✓ During ICRH, ELMs are suppressed, and pedestal coherent mode is enhanced;

✓ Stored energy has a small increase.

➢ Goal:

Reveal the key physical mechanism of ELM suppression by ICRH, and contribute to the ELM control.

[1] X. J. Zhang, et al, Sci. China-Phys. Mech. Astron. 2022.

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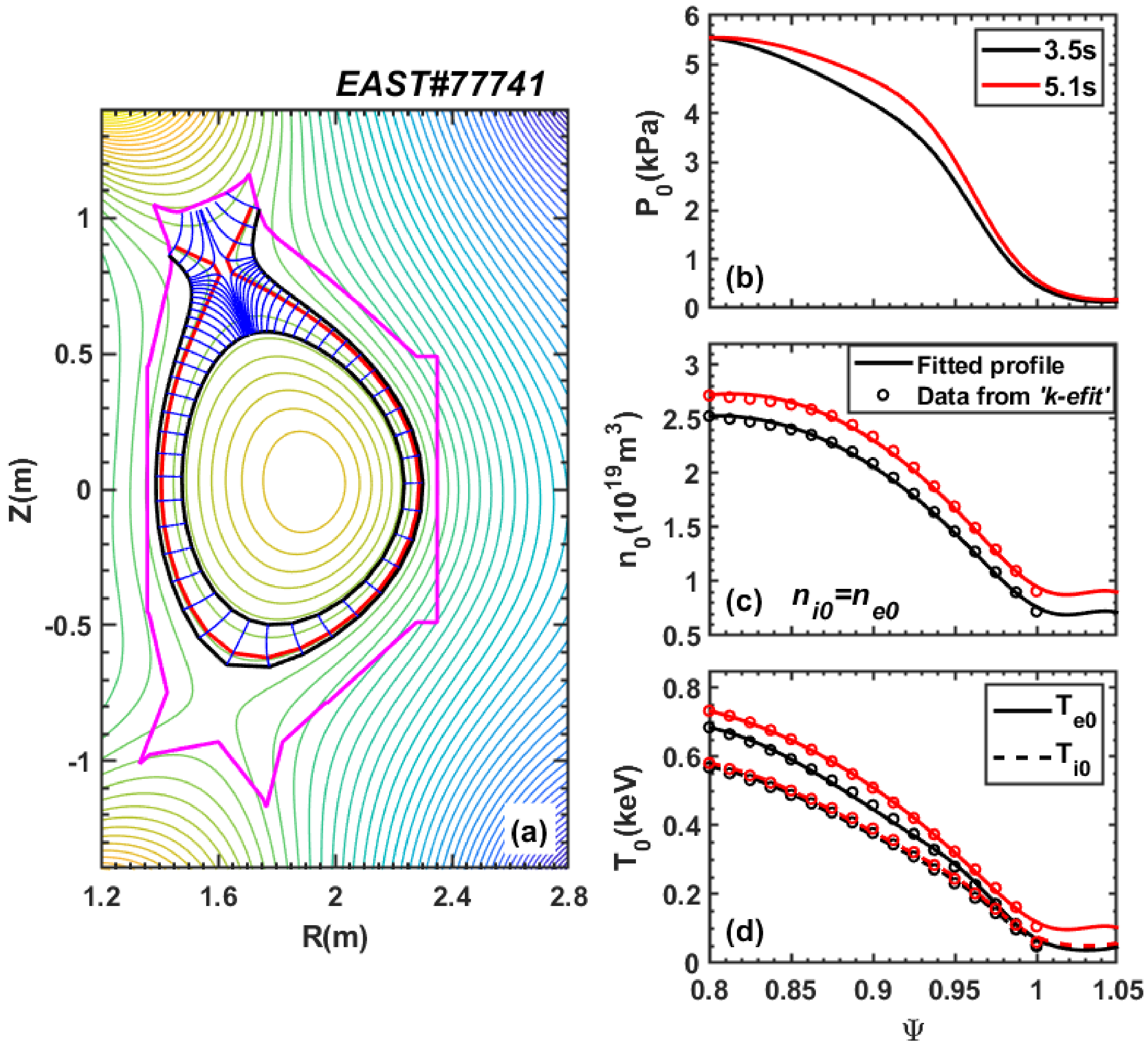
Simulation setup



- **Simulation region：**

  $0.8 < \psi < 1.05$, covering the pedestal and SOL.

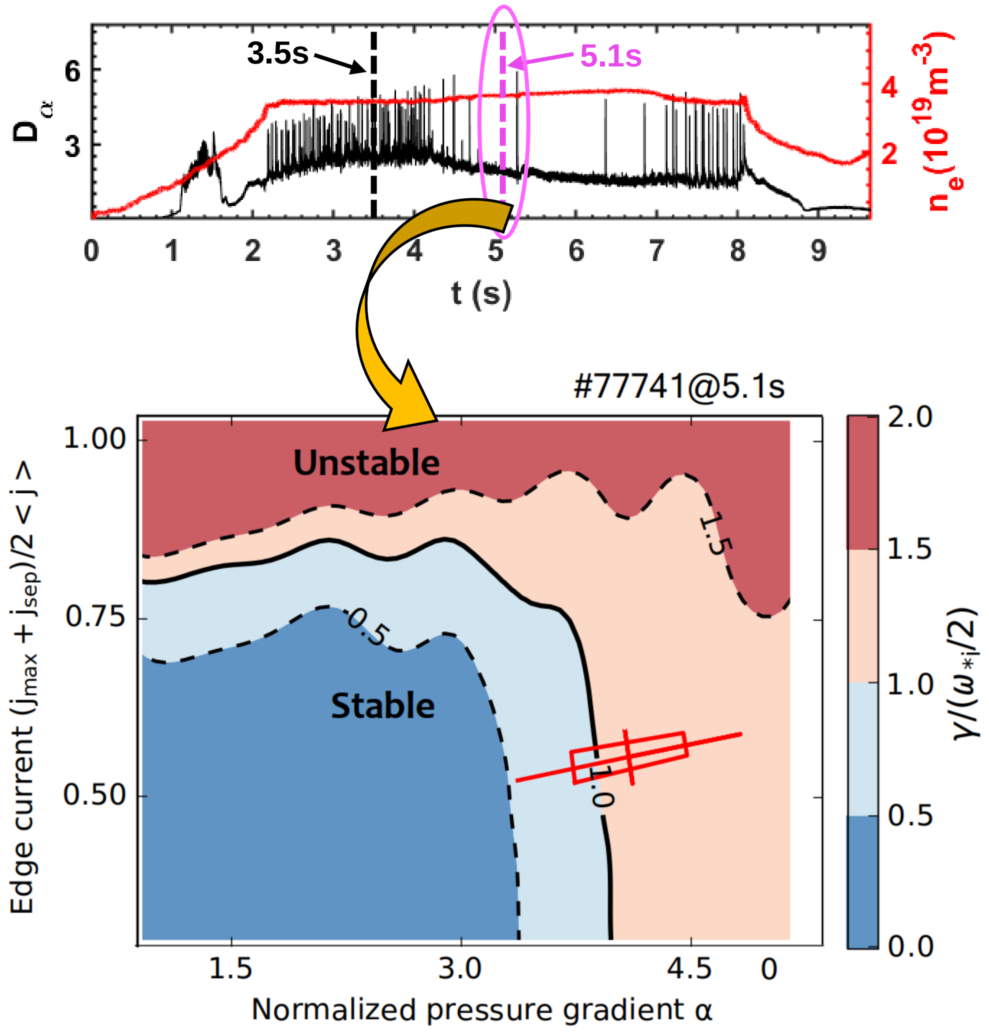
- **During ICRH:**

  T_{e0} and n_0 increase, and the pedestal structure is changed.

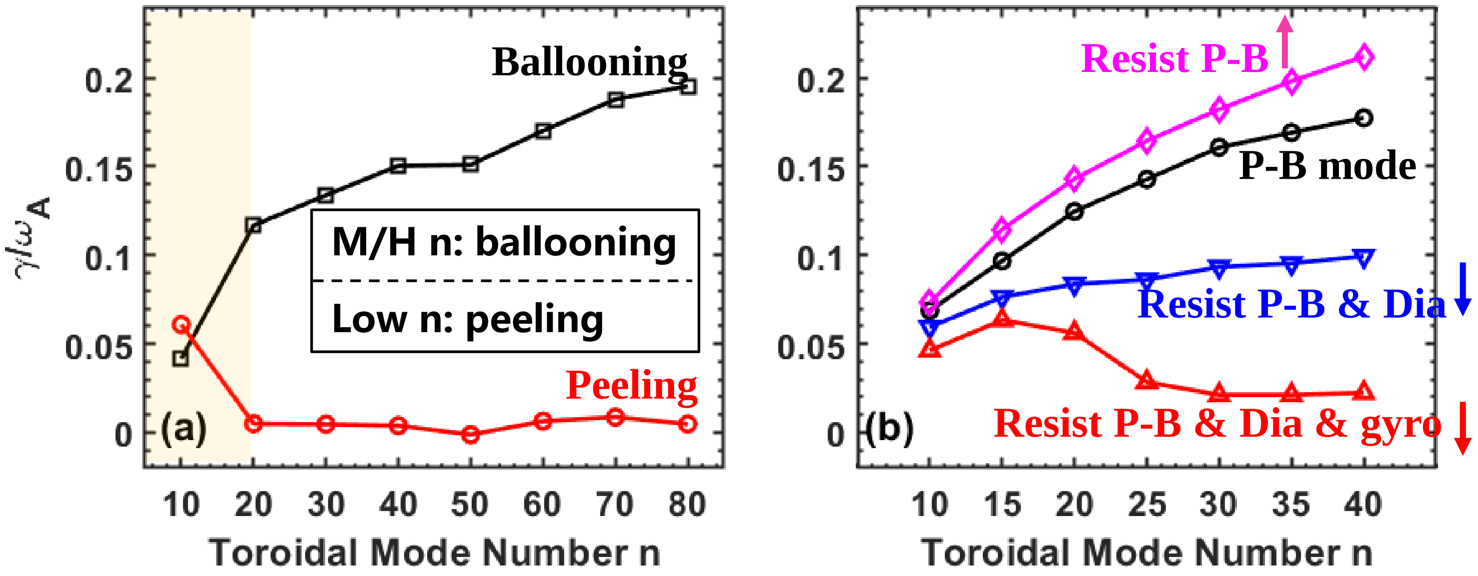
- **Based on the P-B model, including non-ideal physics effects：**
  - Diamagnetic effect
  - $E\times B$ drift
  - Resistivity
  - Hyper-resistivity
  - ……

Pedestal located outside the P-B boundary

➢ **ELITE analysis:**



➢ **BOUT++ linear:**

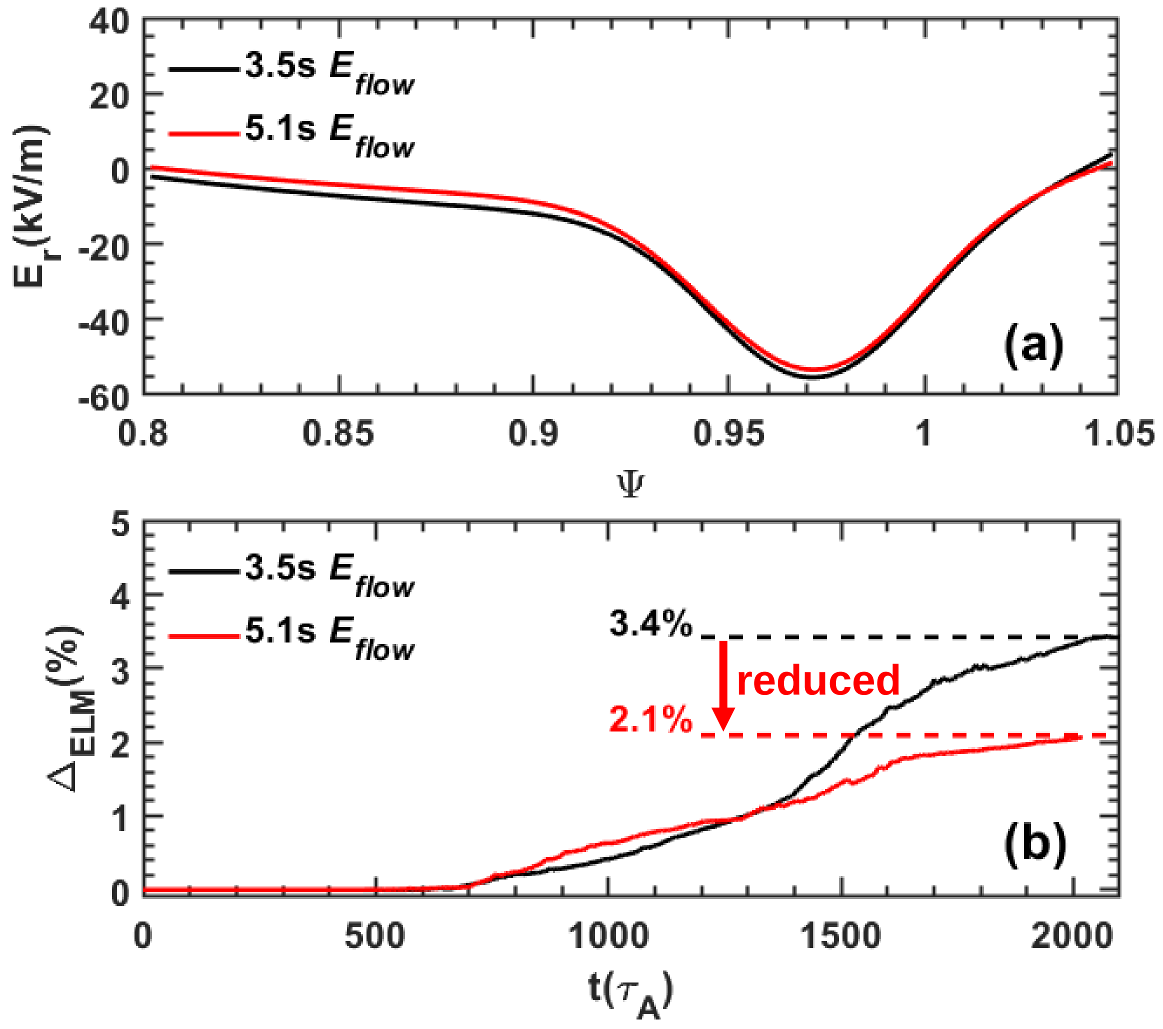


- ☐ **ELITE:** pedestal is located in unstable P-B region;
- ☐ **BOUT++:** γ > 0, the P-B mode is dominant;

✓ **When ELM suppressed (5.1s), pedestal is unstable.**

Little impact of the pedestal structure on ELM

➢ BOUT++ nonlinear:



- **Ratio of ELM energy loss (ELM size):**

$$\Delta_{ELM}^{3D}(t) = \frac{3/2\int_{\psi_{in}}^{\psi_{out}} d\psi \oiint J d\theta d\zeta (P_0 - \langle P(t) \rangle_\zeta)}{3/2\, P_{ped} V_{plasma}}$$

- **Electric field —— flow balance:**

$$E_{flow} = \frac{\nabla P_{i0}}{n_0 Z_i e}$$

◆ **Before ICRH:** $\Delta_{ELM} \sim 3.4\%$;
During ICRH: $\Delta_{ELM} \sim 2.1\%$; ➡ **Relatively large ELM**

◆ **The change of pedestal structure has little impact on ELM suppression.**

No ELM suppression ➡ **RF sheath** ?

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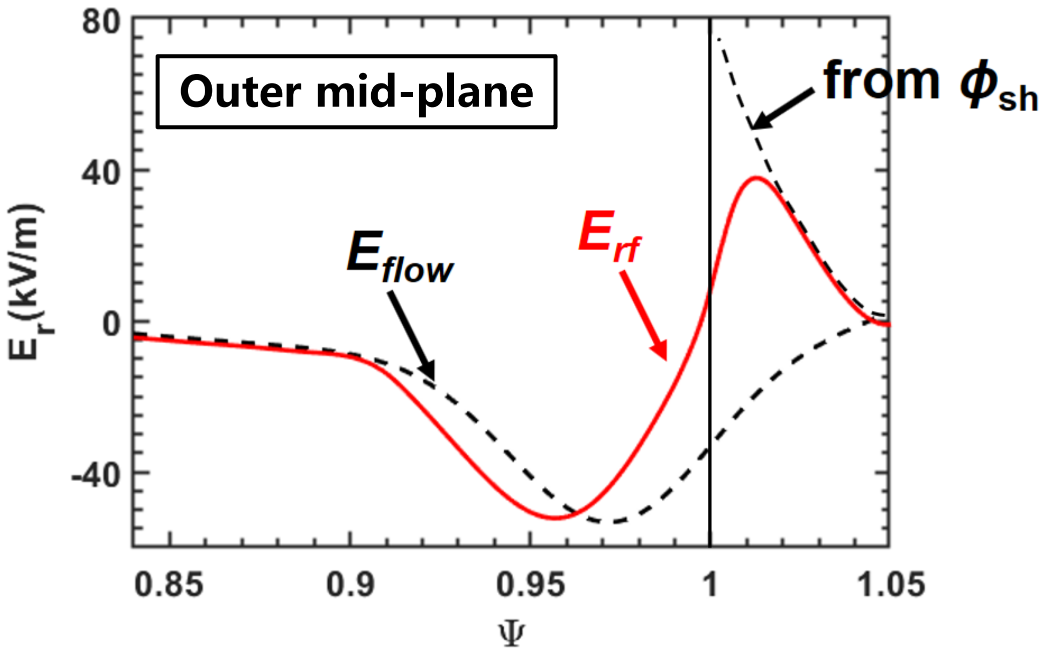
RF sheath model

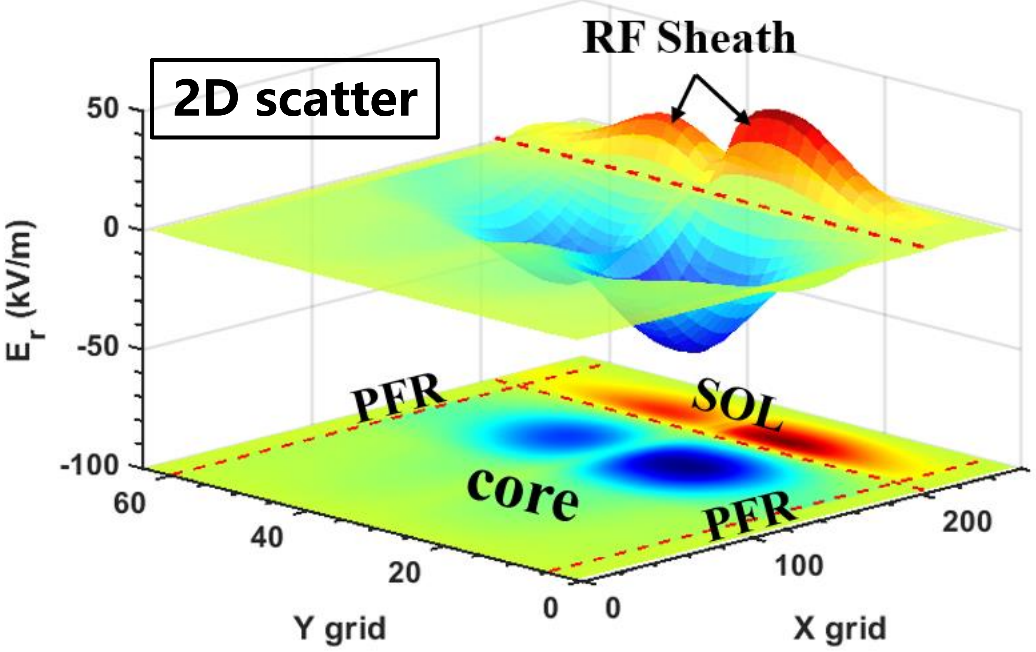
➢ **Physical model[1]:**

- Potential: $\phi_{sh} \sim T_e$
- H mode: large gradient of T_e

Large ϕ_{sh} formed in the SOL

◆ **During ICRH, there is an enhanced edge *E*×*B* shear flow induced by the RF sheath.**



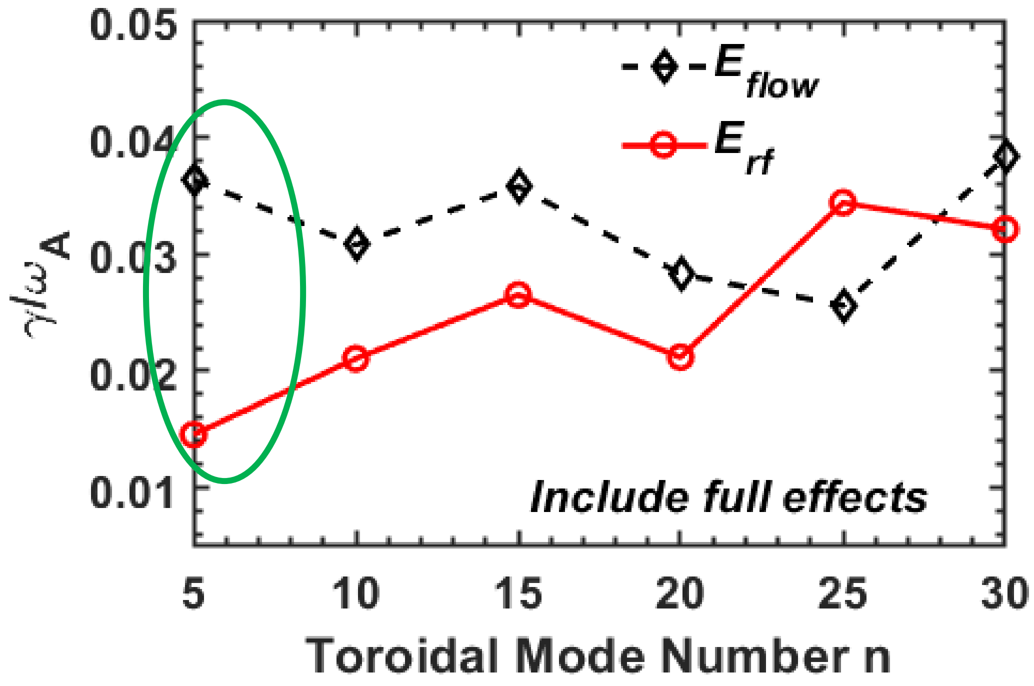


Smoothly connect the flow-balanced E_r and the RF sheath E_r through the separatrix.

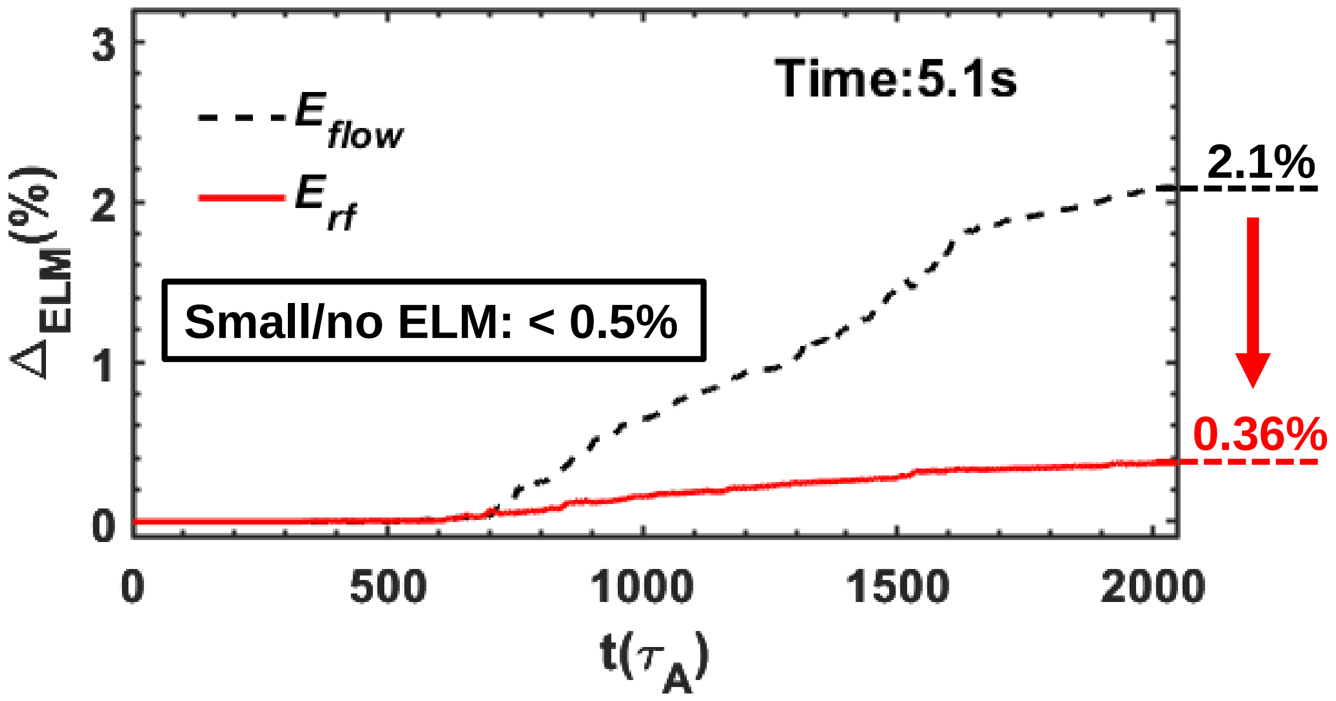
[1] Gui, B., et al. (2018). Nuclear Fusion 58(2).

RF sheath – key factor of ELM suppression

➢ **Linear growth rate:**



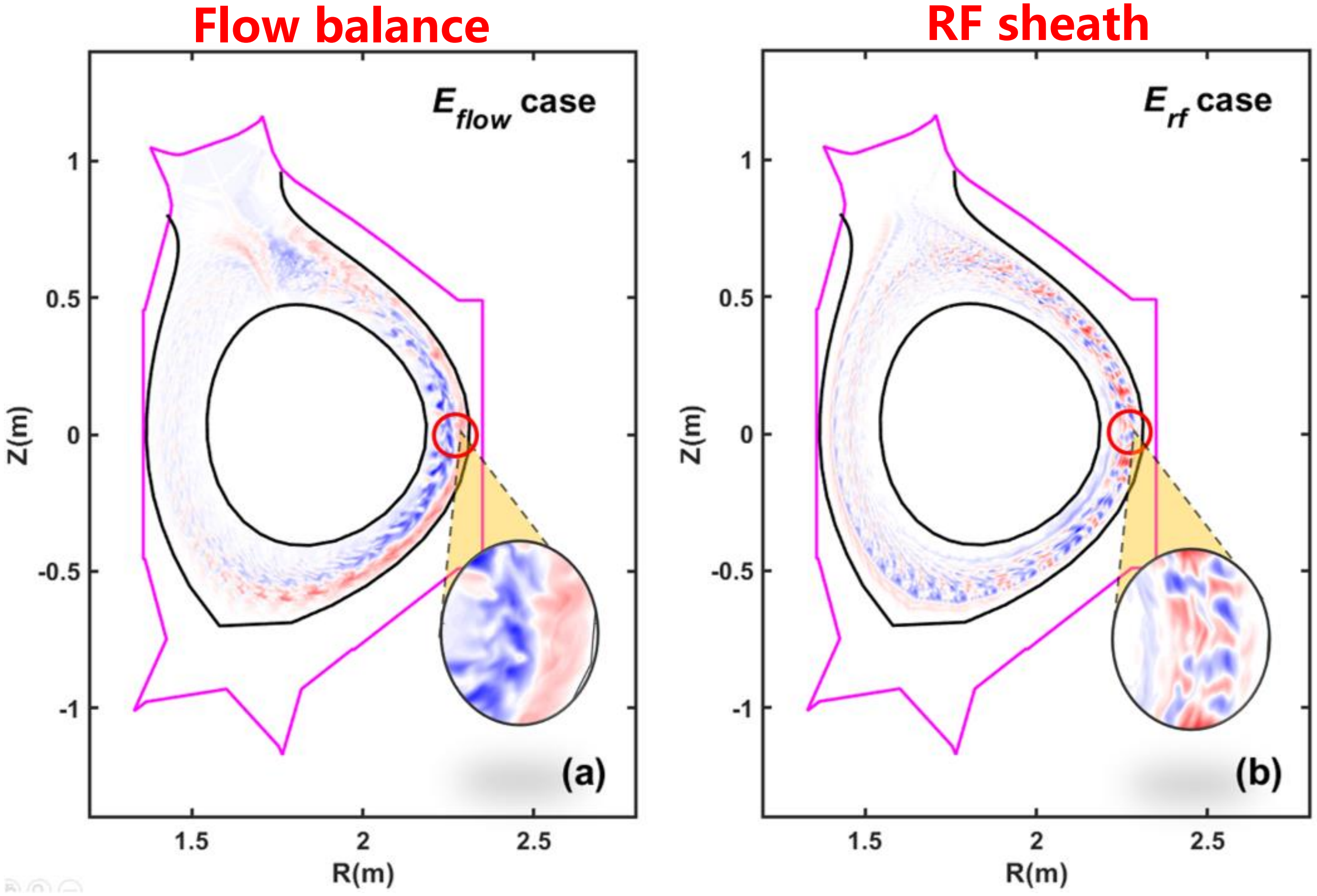
➢ **ELM size:**



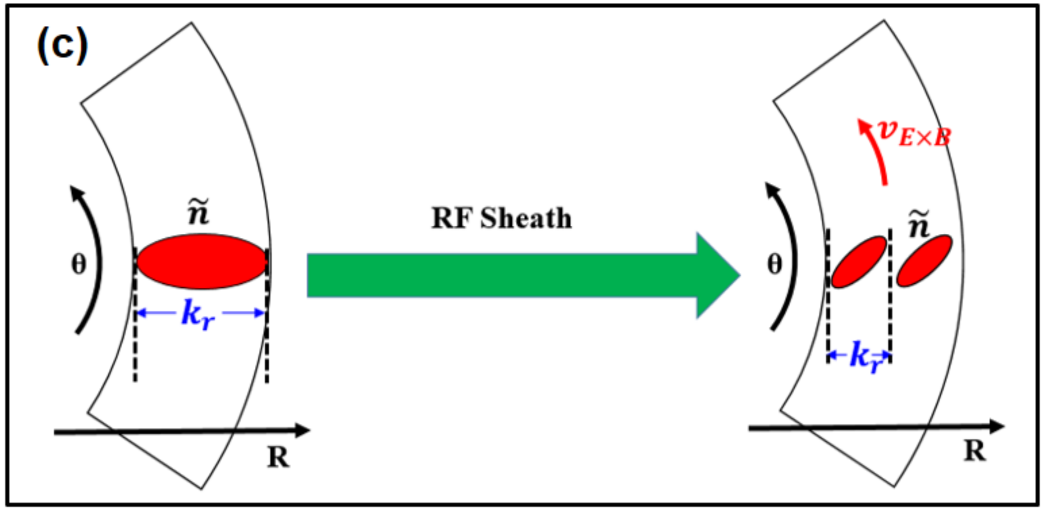
- The RF sheath can reduce the linear growth rate, especially for low-n mode;
- ELM size is reduced from 2.1% to 0.36%, indicating that RF sheath plays a key role in the ELM suppression by ICRH.

Break large-scale filaments into small-scale turbulence

➢ **Poloidal cross section:**



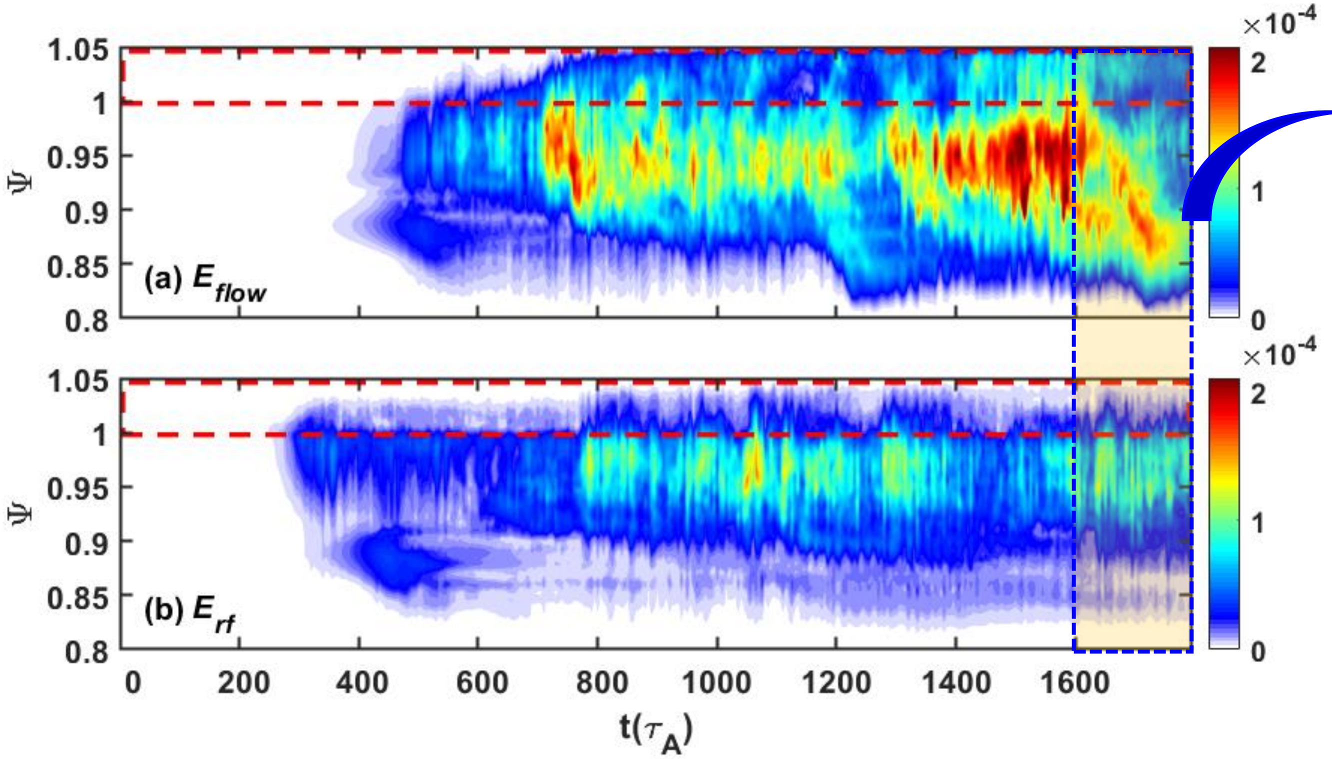
➢ **Schematic Diagram:**

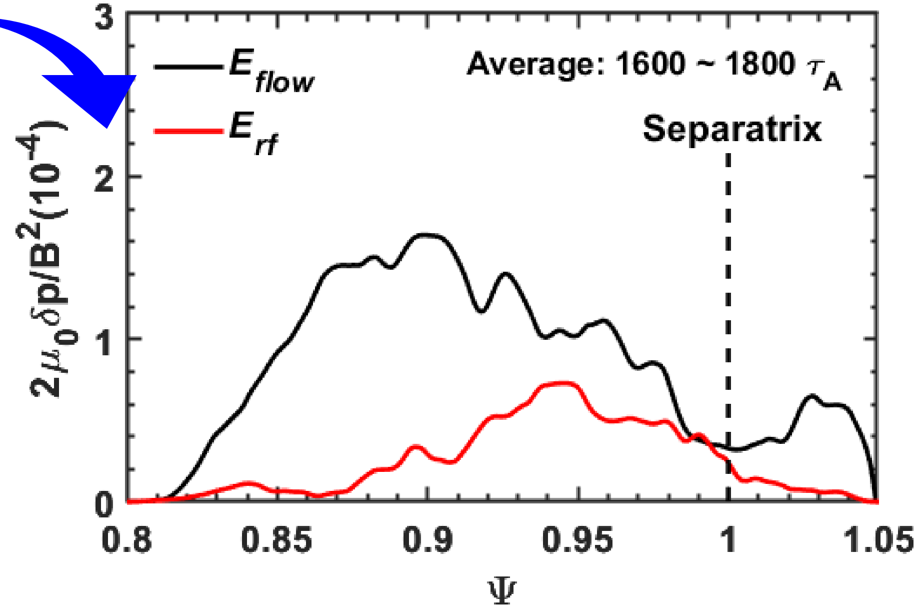


- The larger $E\times B$ shear rate induced by RF sheath breaks up the original large-scale filaments into small-scale turbulence, which can suppress ELM.

Reduce amplitude, suppress radial expansion

➢ **Mode structure of pressure:**

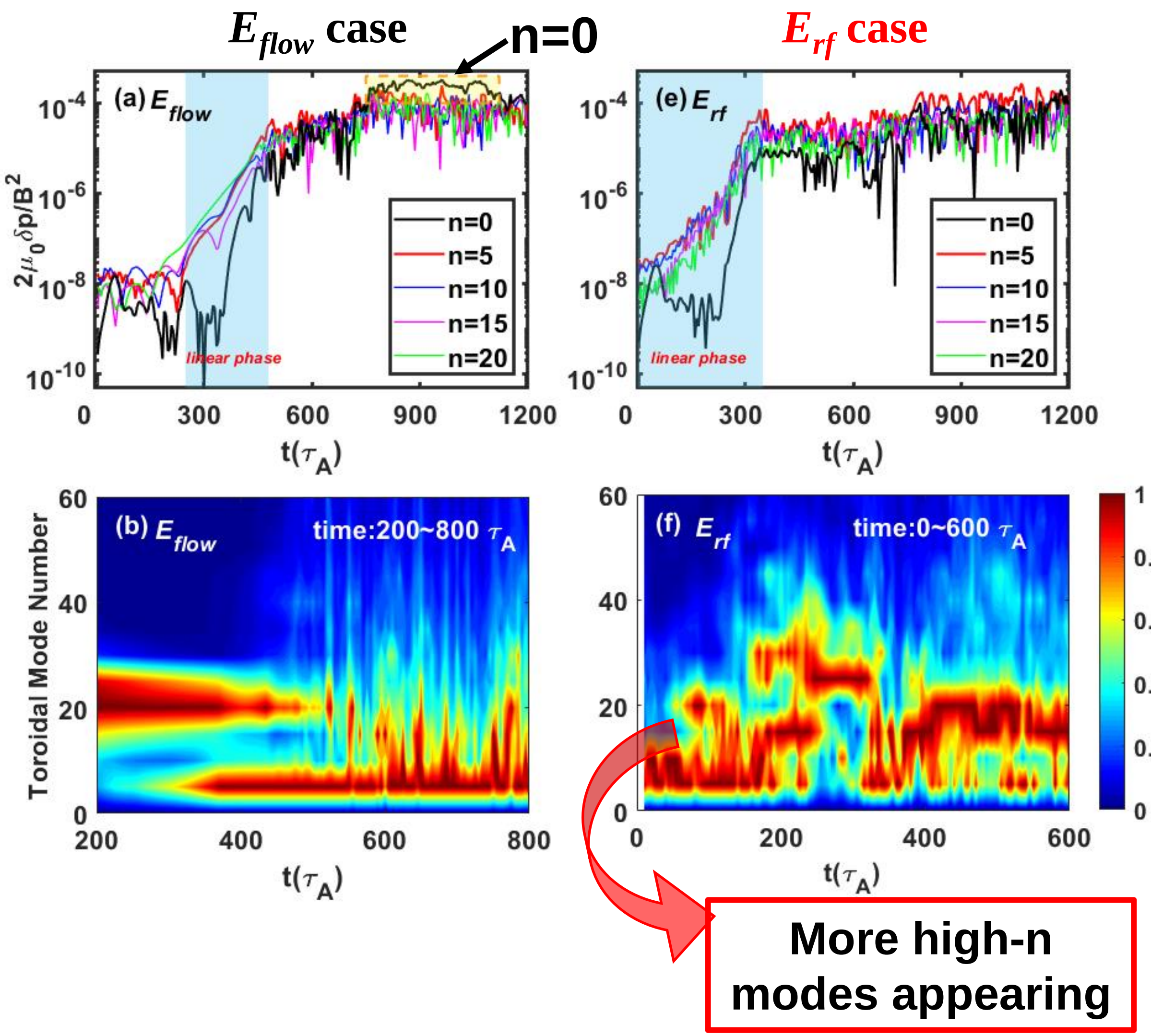




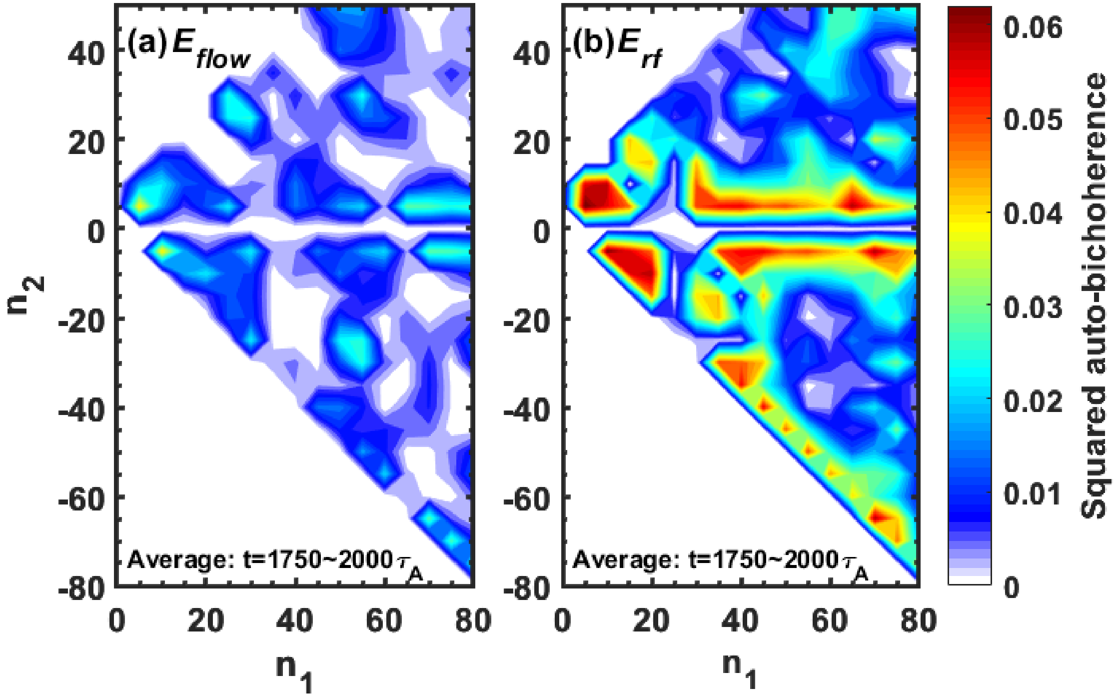
- ☐ With RF sheath, the amplitude is about half smaller;
- ☐ With RF sheath, the radial expansion is suppressed effectively.

More high-n modes appear and stronger mode coupling

- **Perturbed pressure:**



- **Bi-spectral analysis:**



$$\hat{B}_{XYZ}(n_1,n_2) = \langle X(n_1)Y(n_2)Z^*(n_1+n_2)\rangle.$$

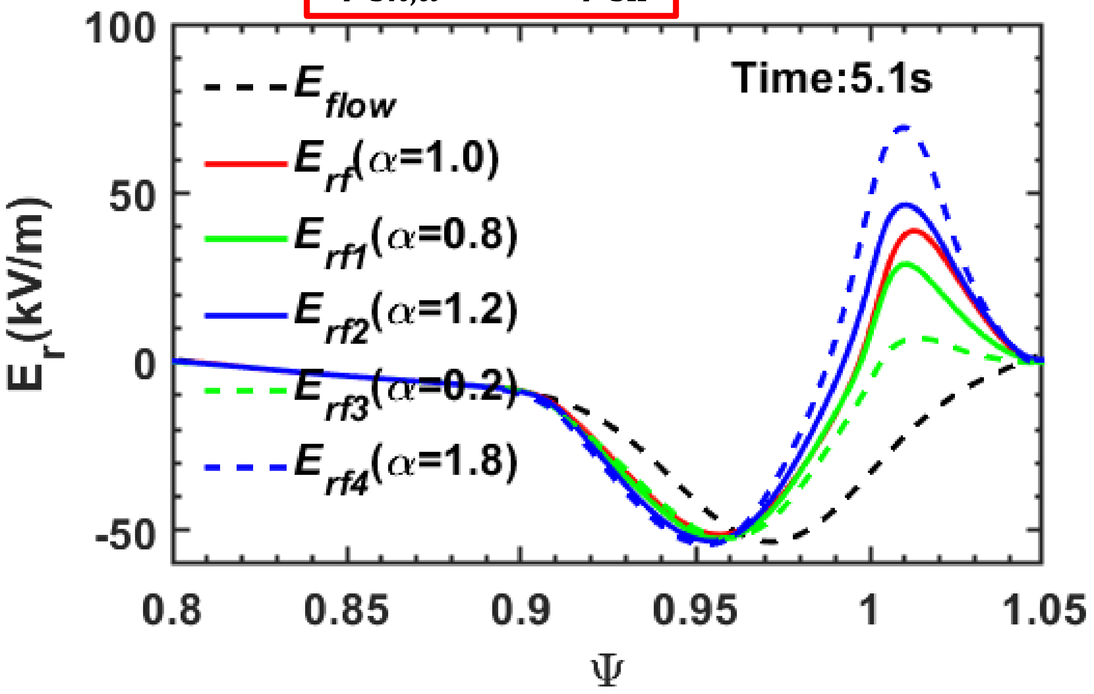
$$\hat{b}^2_{XYZ}(n_1,n_2) = \frac{\left|\hat{B}_{XYZ}(n_1,n_2)\right|^2}{\langle|X(n_1)Y(n_2)|^2\rangle\langle|Z(n_1+n_2)|^2\rangle}.$$

- There are more high-n modes and stronger mode coupling in the E_{rf} case.

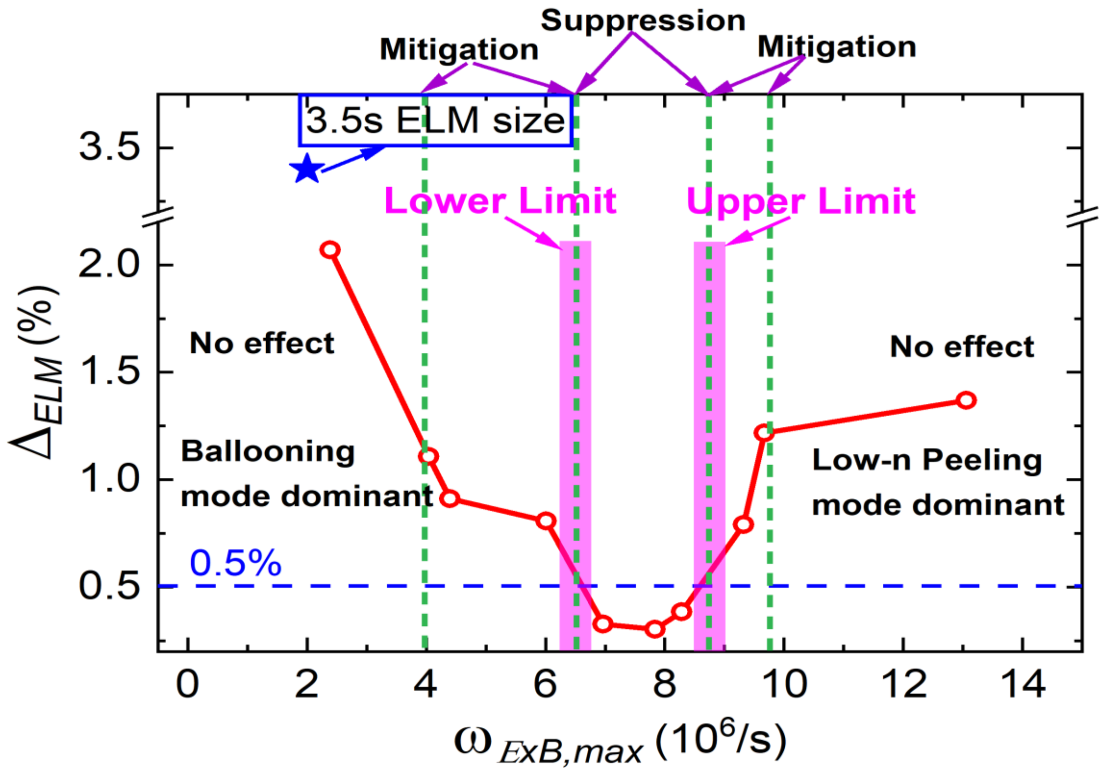
The window exists for ELM suppression by ICRH

- **Scan of RF sheath potential:**

$$\phi_{sh,\alpha} = \alpha \cdot \phi_{sh}$$



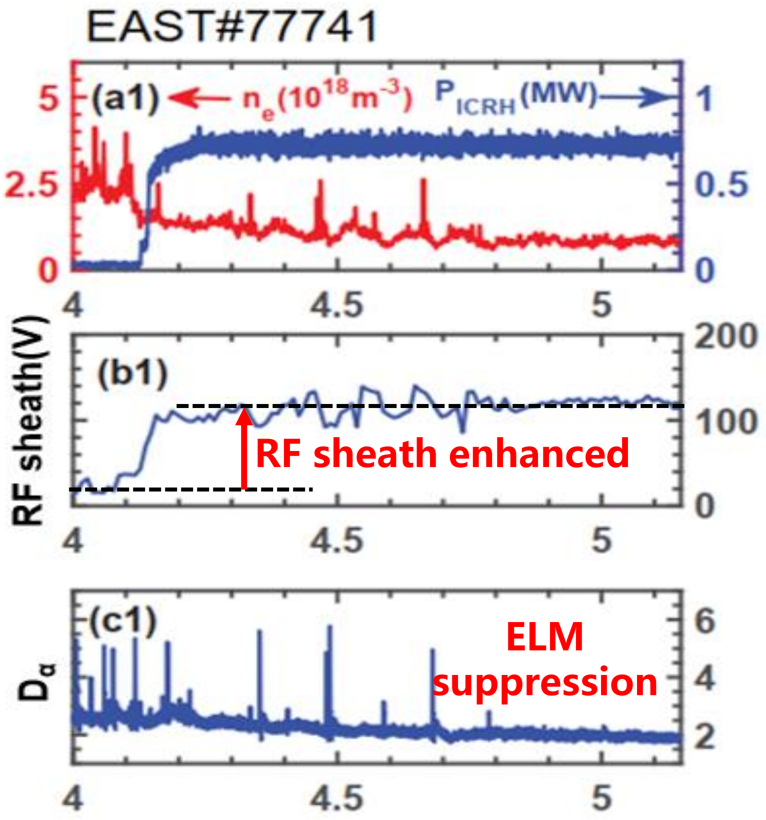
- **Window of ELM suppression:**



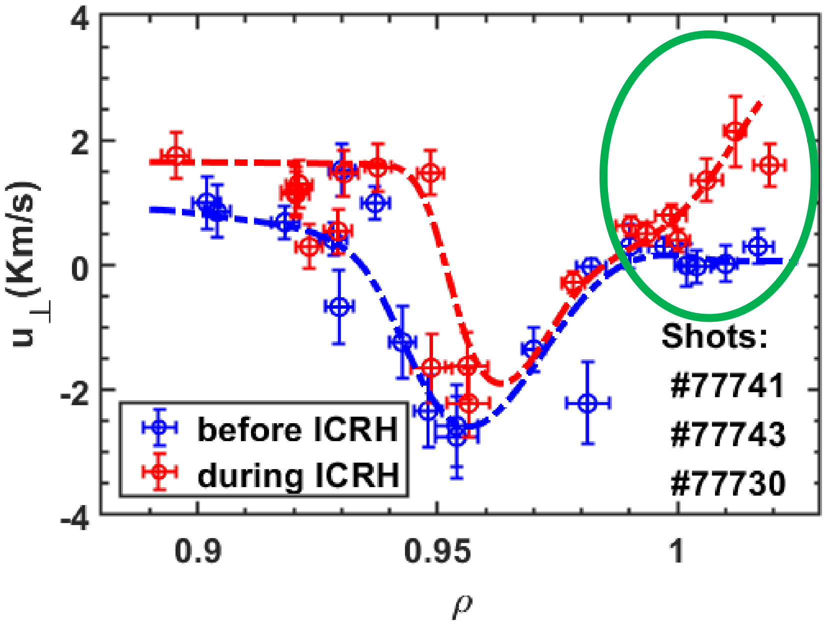
- A small sheath potential window exists for the ELM suppression by ICRH；
- $\omega_{E\times B}$ **too small:** ballooning mode is dominant, and ELM can't be suppressed well;
- $\omega_{E\times B}$ **too large:** peeling mode is triggered, and lead to a large ELM crash.

Validation between simulation and experiment

- **Experiment analysis:**



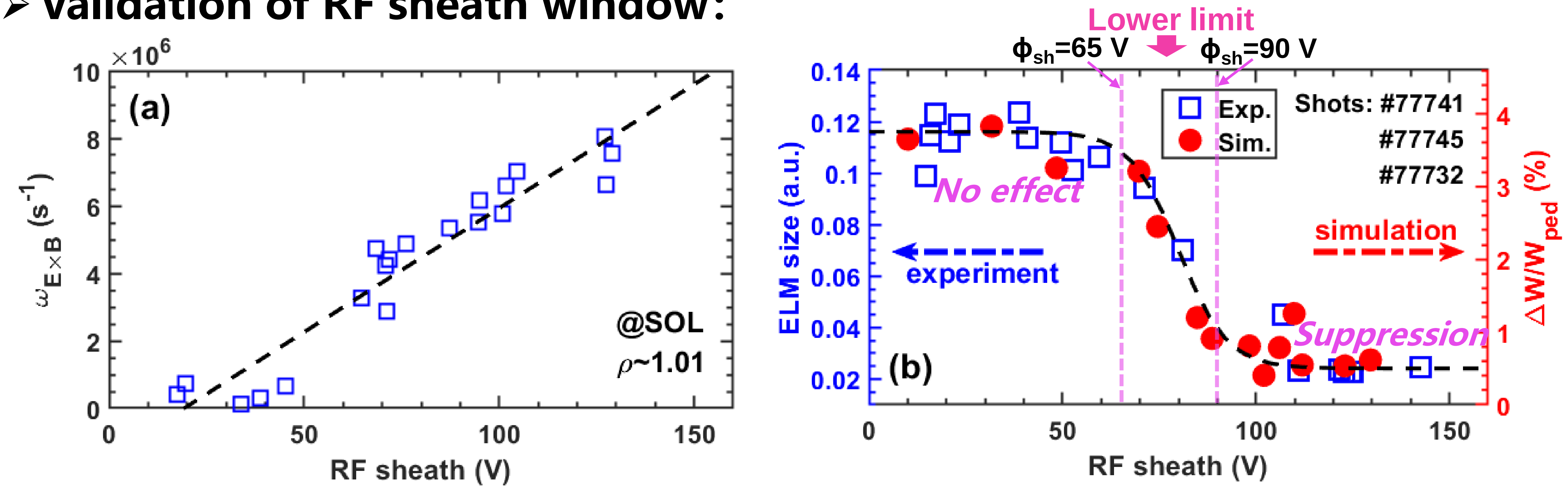
- **U⊥ measured by DBS:**
  - **The U⊥ increases significantly during ICRH.**



- **Relationship:** when RF sheath potential increases, ELM is effectively suppressed；
- **DBS:** During ICRH, the shear velocity ($U_\perp$) in SOL obviously increases, which is consistent with the simulation result.

Validation between simulation and experiment

➢ **Validation of RF sheath window:**



Statistical analysis of experiments:

- A positive correlation between $E\times B$ shear rate in SOL and RF sheath potential;
- The **lower limit** of RF sheath potential was found for ELM suppression;
- Due to the limitation of experiments, the **upper limit** has not been observed.

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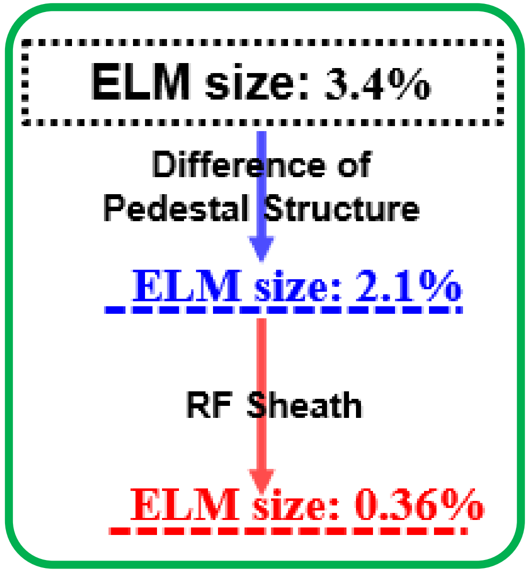
Summary

Phenomenon: ELM can be suppressed by ICRH in EAST;

Little impact of pedestal structure: Δ_{ELM} ~ 3.4% → 2.1%;

Key factor – RF sheath: Δ_{ELM} ~ 2.1% → 0.36%;



The impact of RF sheath:

- Reduce the linear growth rate and perturbed amplitude;
- Larger $E\times B$ shear flow, break up the large-scale filaments;
- Stronger nonlinear mode coupling;

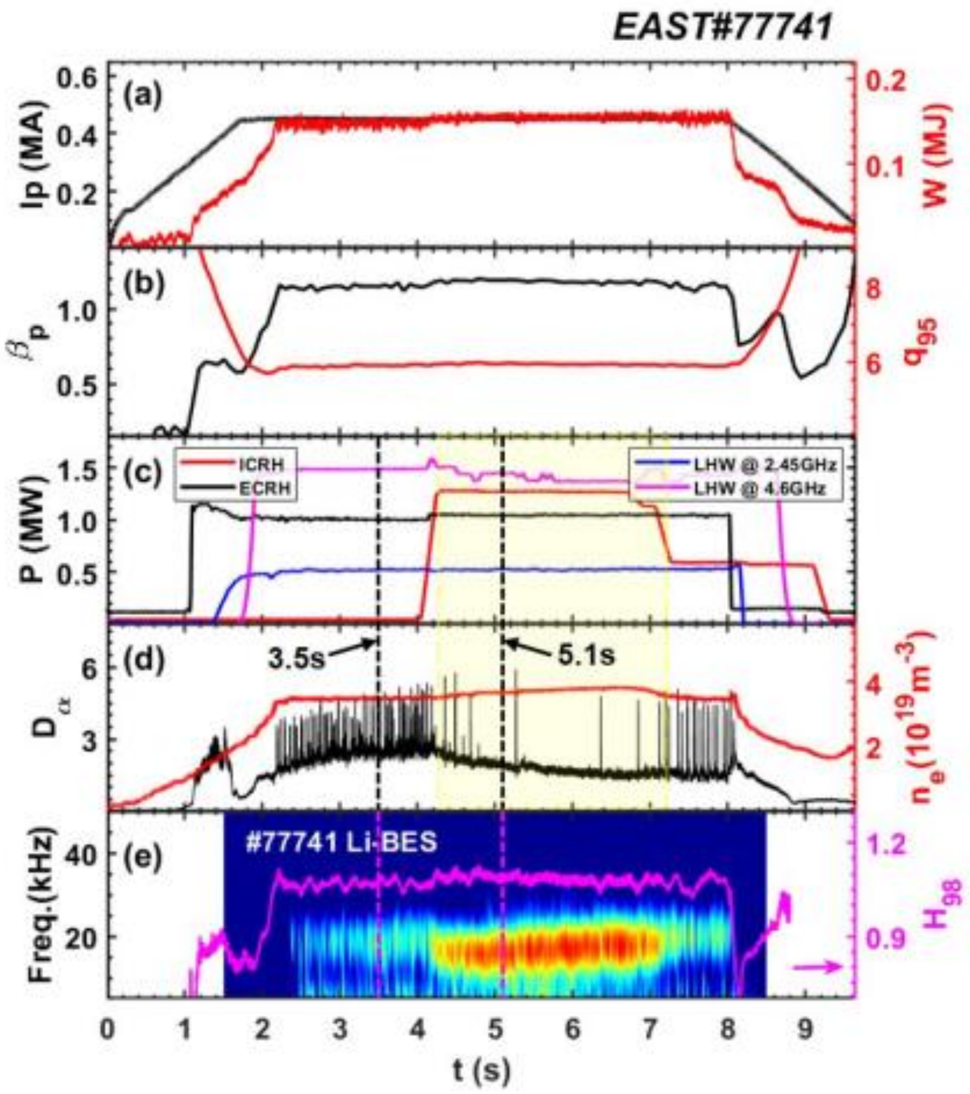
Scan the RF sheath potential:

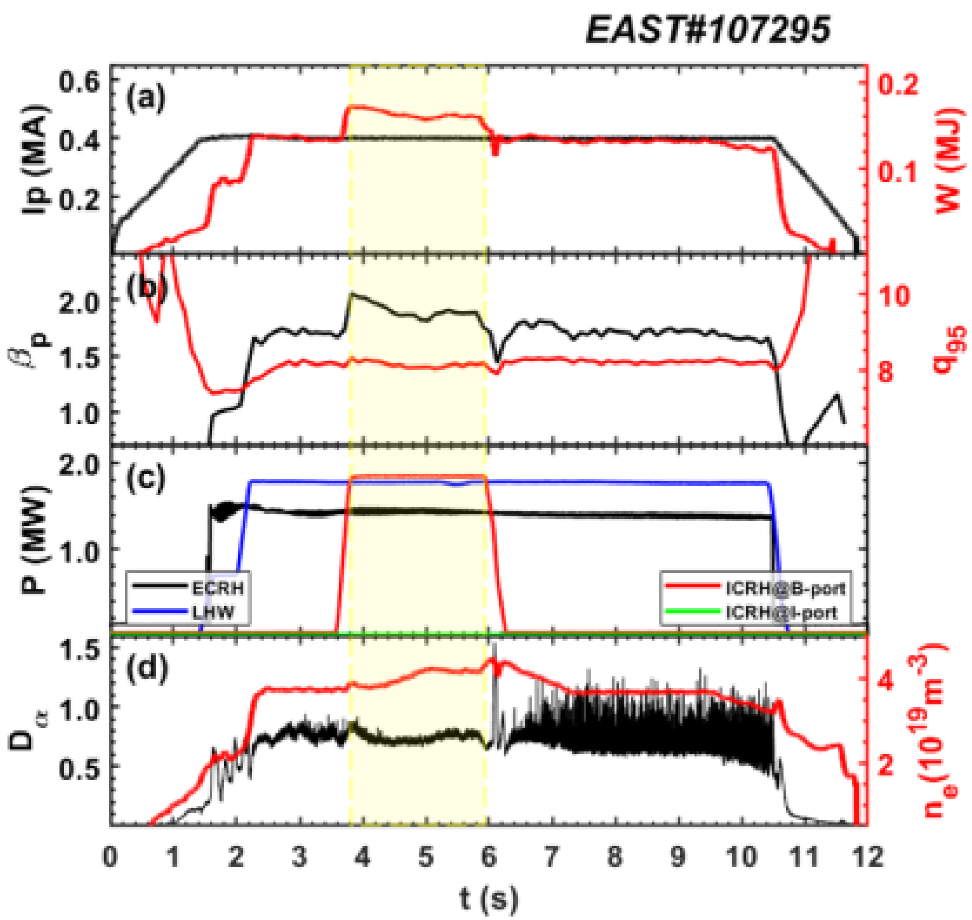
- A small window of $\omega_{E\times B}$ exists for full ELM suppression by ICRH;
- $\omega_{E\times B}$ small: ballooning mode; $\omega_{E\times B}$ large: peeling mode;
- The existence of window has been validated in the experiments.

Thank You!

BACKUP SLICES

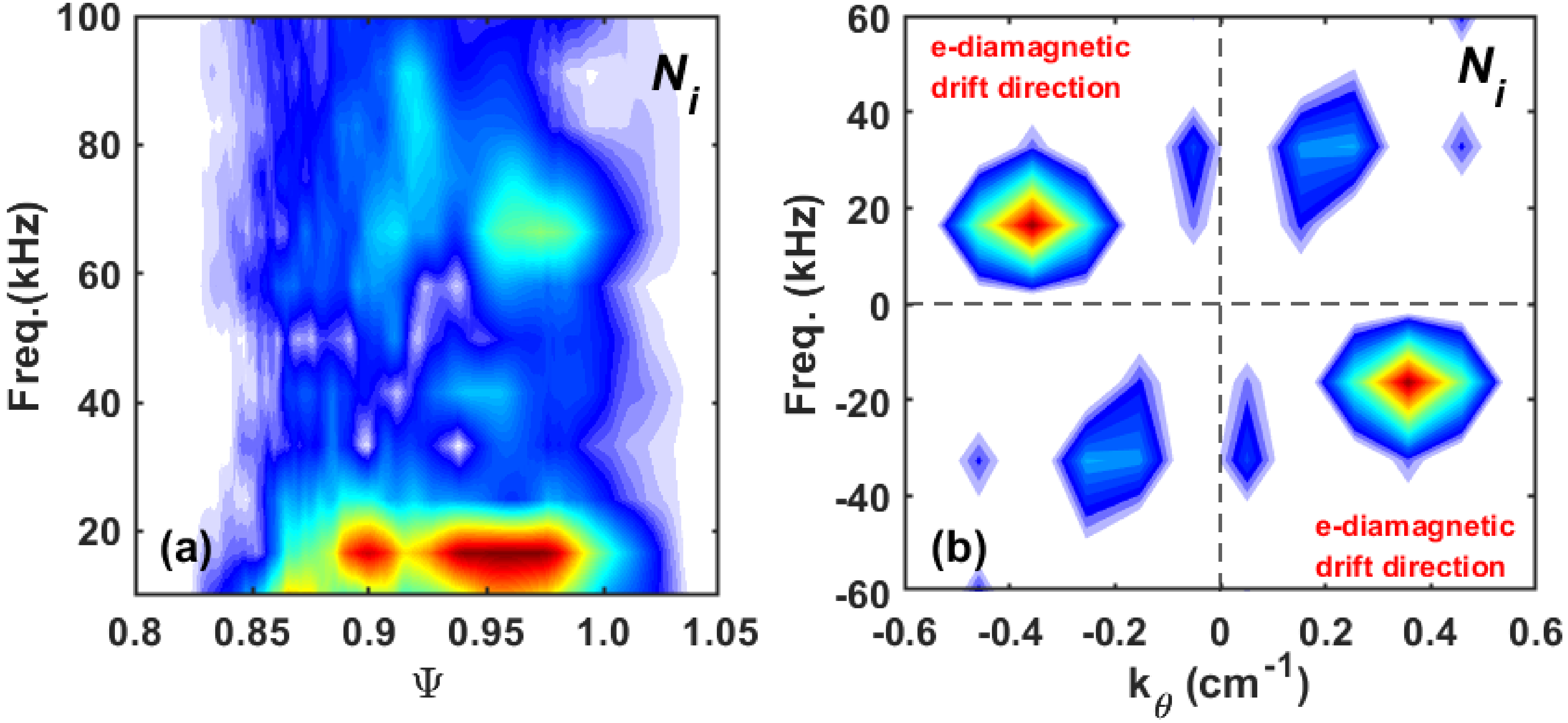
Why no ICRF heating effect is observed?





- **Old ICRH:** the heating effect of the ICRH is not obvious, and the ion temperature has little change.
- **New ICRH:** with smaller $k_{||}$ ~ 7.5 m^{-1}, has a much higher coupling loading. The coupling loading and heating efficiency of the new ICRH are ~ 3-7 times greater than the old.

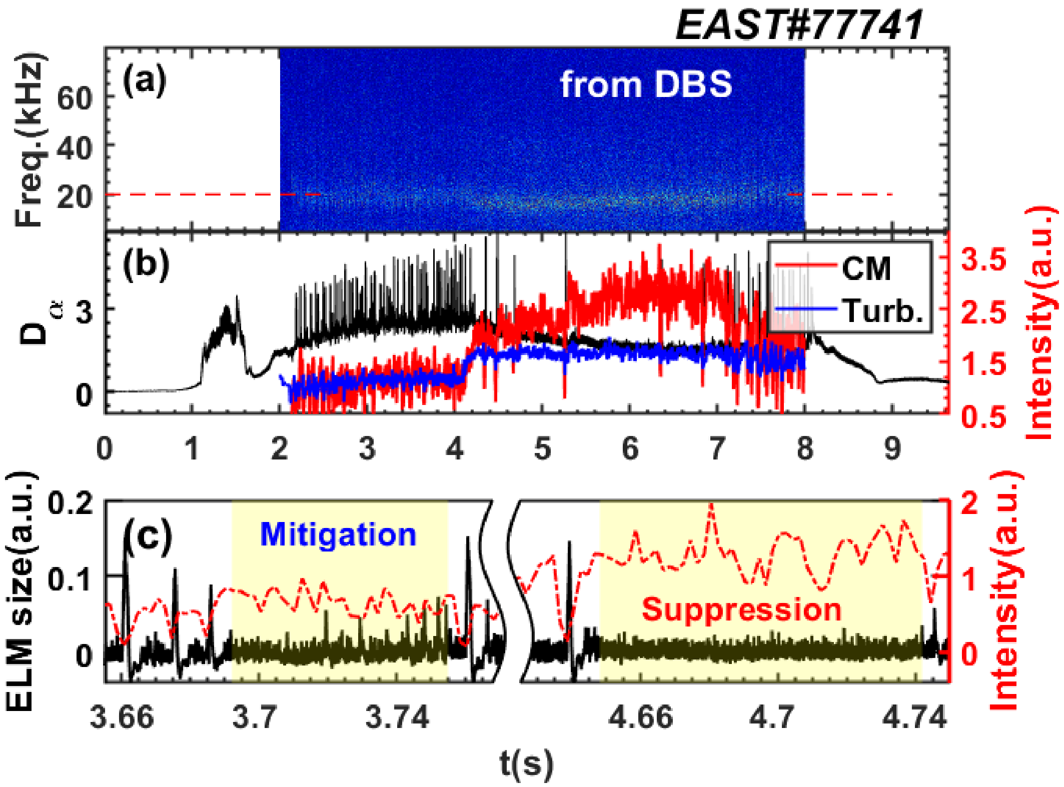
Simulation results of the CM

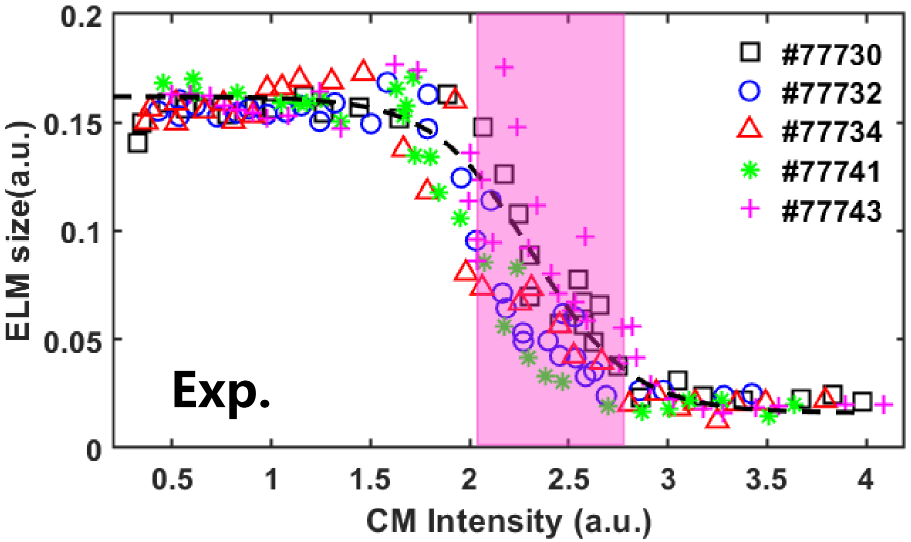


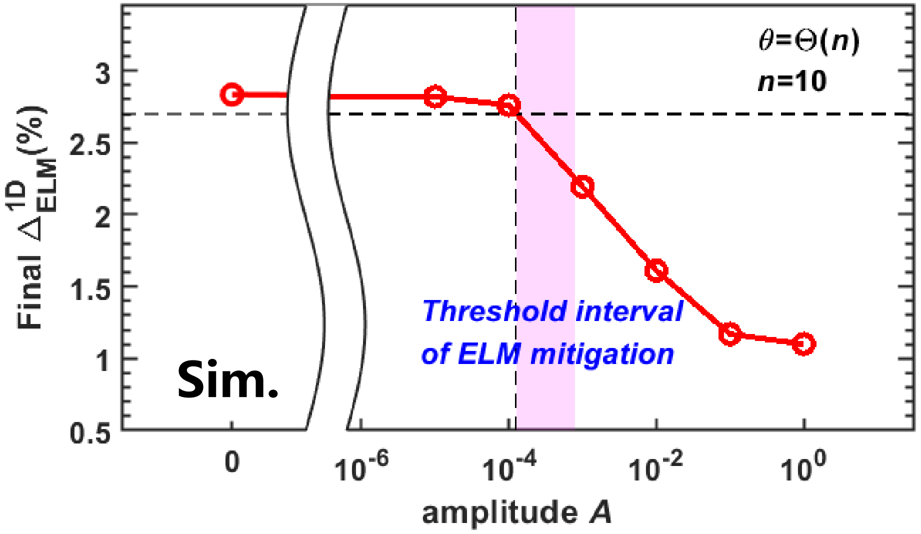
Ni	Simulation	Experiment
Frequency(kHz)	16.34	15 – 20
k_θ (rad cm^{-1})	0.36	0.3 – 0.5

- The simulated CM: f ~ 16.34 kHz, k_θ ~ 0.36 cm^{-1};
- Results are consistent with the experiment.

Effect of CM on the ELM suppression







- The strong correlation between CM intensity and ELM size;
- There is a threshold value of CM intensity for ELM suppression;
- The simulation is consistent with the experiment;
- There is a stronger mode coupling with CM.

[Y.L. Li et al 2022 Nucl. Fusion 62 066018]

The effect of the impurity

The vorticity equation with background impurity is modified to

T. Y. Xia, et al. US/EU Transport Task Force Workshop, Salem, MA, 2015

$$
\begin{aligned}
\frac{\partial}{\partial t}\varpi &= -\left(\frac{1}{B_0}\boldsymbol{b}\times\nabla_\perp\Phi + V_{\|i}\boldsymbol{b}\right)\cdot\nabla\varpi + B^2\nabla_\|\left(\frac{J_\|}{B}\right) + 2\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\nabla p_1 \\
&-\frac{1}{2\Omega_i}\left[\frac{1}{B}\boldsymbol{b}\times\nabla P_i\cdot\nabla\left(\nabla_\perp^2\Phi\right) - Z_i eB\boldsymbol{b}\times\nabla n_i\cdot\nabla\left(\frac{\nabla_\perp\Phi}{B}\right)^2\right] \\
&+\frac{1}{2\Omega_i}\left[\frac{1}{B}\boldsymbol{b}\times\nabla\Phi\cdot\nabla\left(\nabla_\perp^2 P_i\right) - \nabla_\perp^2\left(\frac{1}{B}\boldsymbol{b}\times\nabla\Phi\cdot\nabla P_i\right)\right] \\
&-\frac{1}{2\Omega_{im}}\left[n_{im}Z_{im}e\boldsymbol{V}_{Dim}\cdot\nabla\left(\nabla_\perp^2\Phi\right) - m_{im}\Omega_{im}\boldsymbol{b}\times\nabla n_{im}\cdot\nabla V_E^2\right] \\
&+\frac{1}{2\Omega_{im}}\left[\boldsymbol{V}_E\cdot\nabla\left(\nabla_\perp^2 P_{im}\right) - \nabla_\perp^2\left(\boldsymbol{V}_E\cdot\nabla P_{im}\right)\right].
\end{aligned}
$$

$$
\begin{aligned}
\varpi &= \boldsymbol{b}\cdot\nabla\times\left(m_i n_i V_i + m_{im}n_{im}V_{im}\right) \\
&\simeq n_{i0}\frac{m_i}{B_0}\left(\nabla_\perp^2\phi + \frac{1}{n_{i0}}\nabla_\perp\phi\cdot\nabla_\perp n_{i0} + \frac{1}{n_{i0}Z_i e}\nabla_\perp^2 p_{i1}\right) \\
&+n_{im}\frac{m_{im}}{B_0}\left(\nabla_\perp^2\phi + \frac{1}{n_{im}}\nabla_\perp\phi\cdot\nabla_\perp n_{im}\right).
\end{aligned}
$$

Gyro-viscous

Quasi-neutral condition

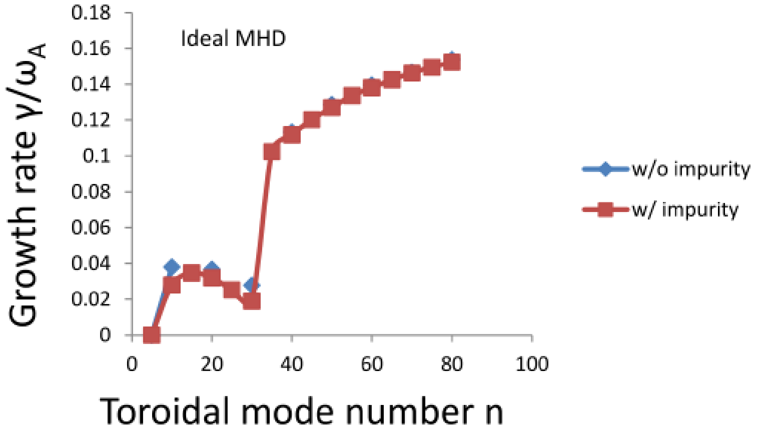
$$
\begin{aligned}
Z_i n_{i0} + Z_{im}n_{im} &= n_{e0} \\
n_j &= n_{j0} + n_{j1}, \\
P_j &= P_{j0} + p_{j1}, \\
P = P_i + P_e \quad + P_{im} &= P_0 + p_1 = (P_{i0} + P_{e0}) + (p_{i1} + p_{e1}) + P_{im}, \\
\Phi &= \Phi_0 + \phi, \\
J_\| &= J_{\|0} + J_{\|1}, \\
V_{\|e} &= \frac{Z_i n_i}{n_e}V_{\|i} - \frac{J_{\|1}}{en_e}, \\
\boldsymbol{b} &= \boldsymbol{b}_0 - \boldsymbol{b}_0\times\nabla\psi, \\
J_{\|1} &= -\frac{1}{\mu_0}B_0\nabla_\perp^2\psi.
\end{aligned}
$$

The effects of impurity: all the terms are at the order of $m_{im}n_{im}$

The effect of the impurity

The background impurity can stabilize the ballooning mode

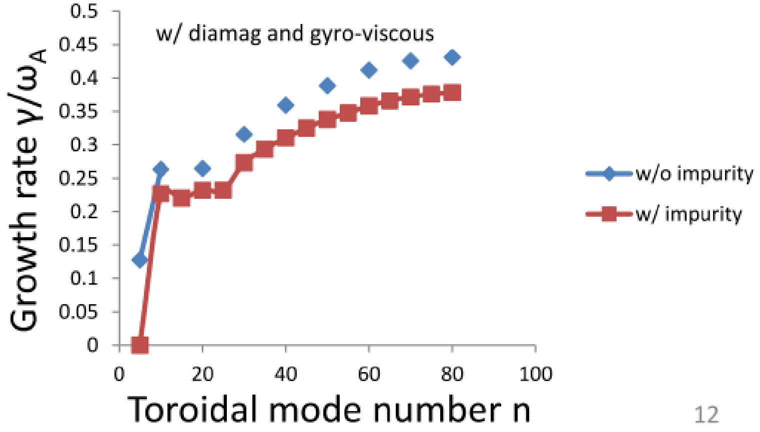
The effects of background impurity (carbon): can be treated as the change of mass density.



If the density profiles is kept unchanged

- ➢ The effects of impurity: decreasing the low-n ballooning modes by ~14%.

- ➢ If w/ both diamagnetic effects and gyro-viscosity, the growth rate for whole n is stabilized by impurity by ~12%, more effectively.



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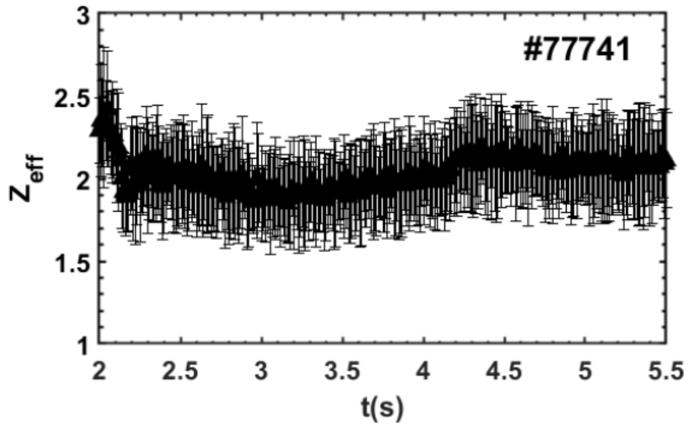
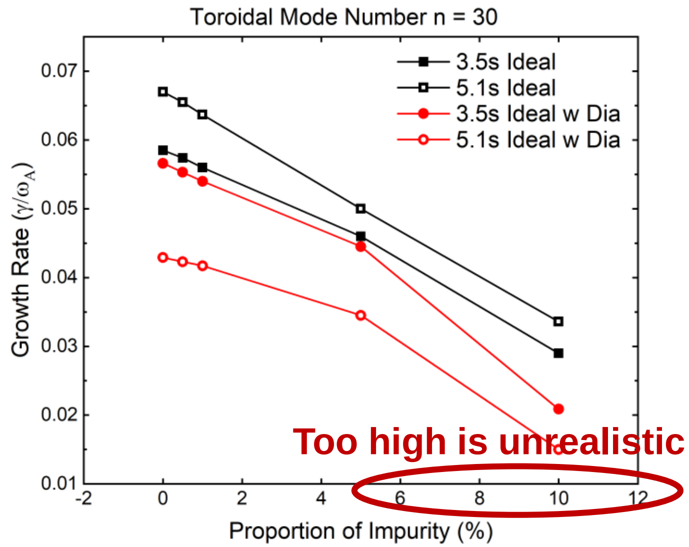
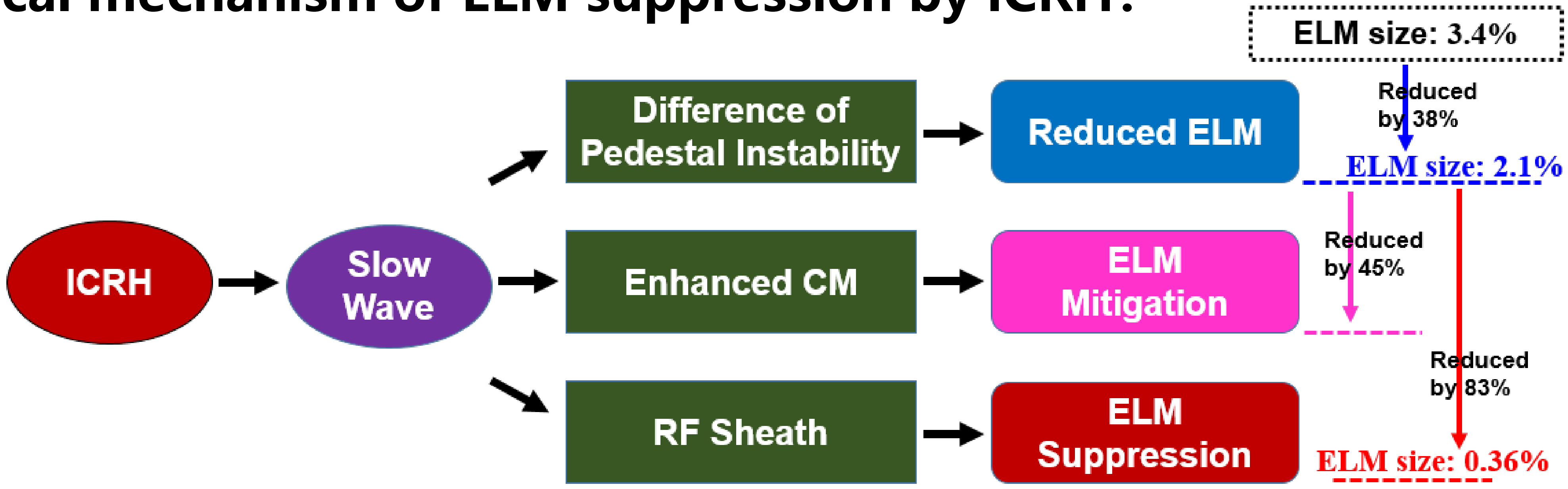




- ☐ Don't show the effect of gyro-viscosity, need more calculations;
- ☐ The more impurities, the smaller the growth rate;

Publication

➢ **Physical mechanism of ELM suppression by ICRH:**



- **Y.L. Li**, T.Y Xia, X.L. Zou, et al. 2022, *Nucl. Fusion*, 62 066043, DOI: https://doi.org/10.1088/1741-4326/ac4efd
- **Y.L. Li**, T.Y Xia, X.L. Zou, et al. 2022, *Nucl. Fusion*, 62 066018, DOI: https://doi.org/10.1088/1741-4326/ac5449
- X. J. Zhang, C. Zhou, X. L. Zou, T. Y. Xia, **Y. L. Li**, et al. 2022, *Sci. China-Phys. Mech. Astron.* 65 235211, DOI: https://doi.org/10.1007/s11433-021-1817-8

Email: yanlong.li@ipp.ac.cn