ELM Control Physics with LHCD and Impurity Seeding in the HL-2A Tokamak

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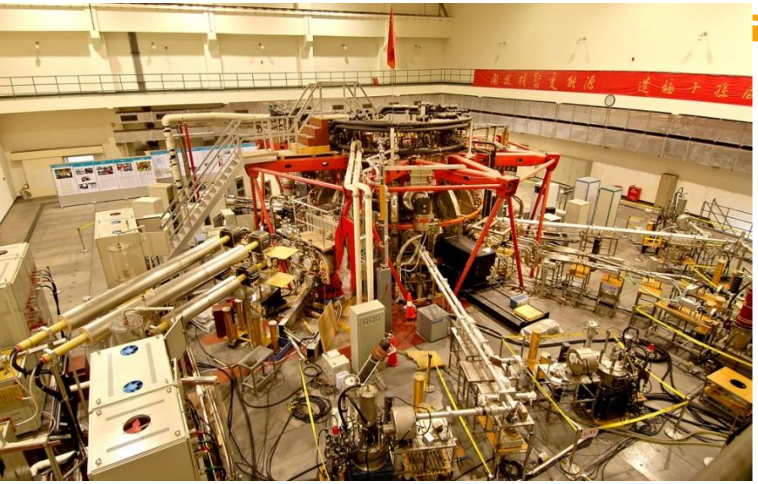


- ☐ Background
- ☐ Experimental results
- ☐ Theoretical simulation
- ☐ Summary

Background

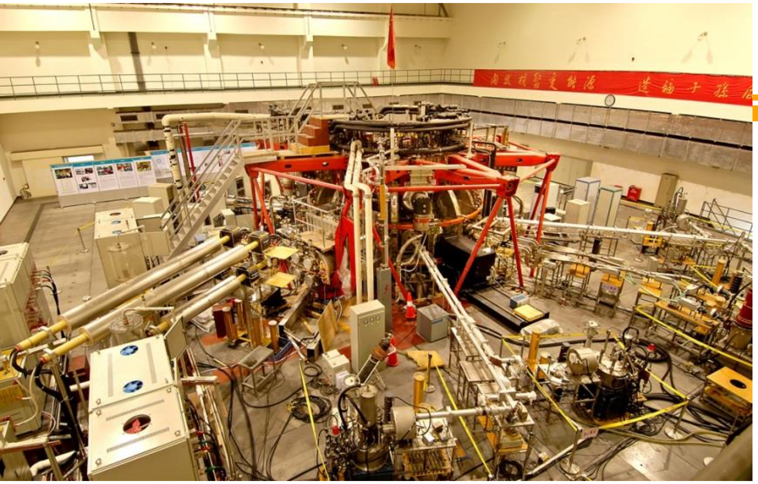
ELM and Heat flux control for ITER

- ✓ Simulations and scaling have predicted that in magnetic fusion reactor as ITER, the divertor heat flux caused by large ELMs are far beyond the material limitation, and can cause severe erosion on plasma facing components.
- ✓ Effective techniques are highly desirable to achieve external control of the ELM size and the heat load.

Existing mitigation techniques

- ✓ ELM mitigation techniques :Pellet pacing, SMBI, RMP and other perturbation fields.
- ✓ Recently lower hybrid current drive (LHCD) has been shown to be a new effective method for ELM mitigation.

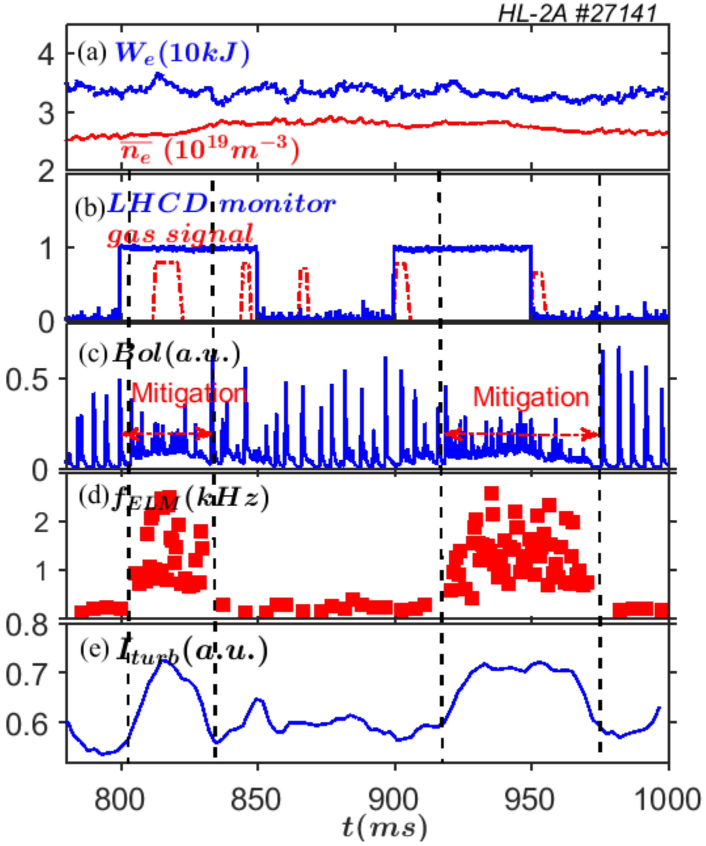
- ☐ Nevertheless, the reliability of these methods still needs to be demonstrated, and the understanding of the mechanism requires further investigation.
- ☐ ELM mitigation seems to be strongly correlated to pedestal turbulence enhancement from the previous results in HL-2A.



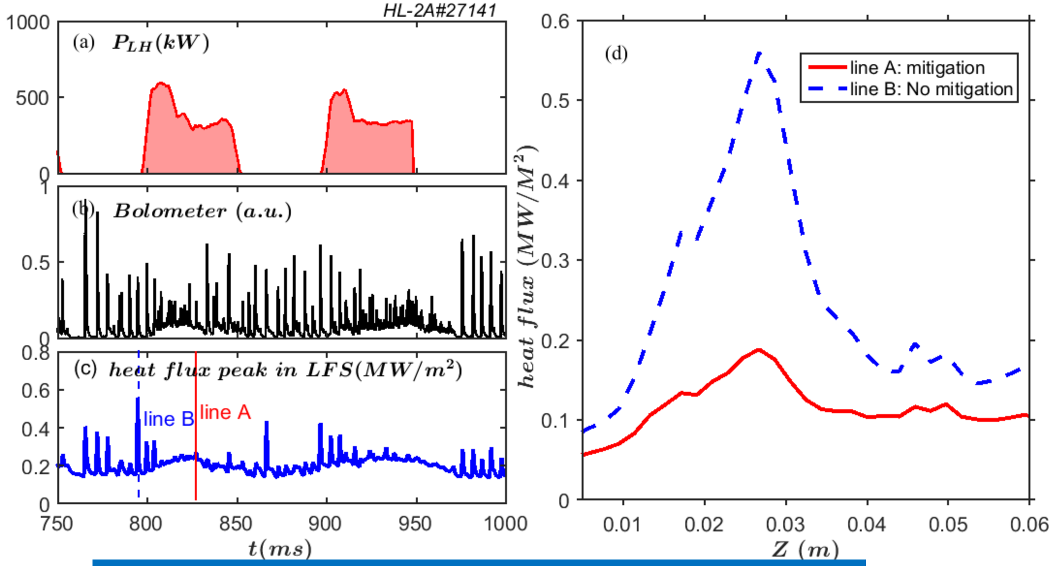
Ⅱ. Experimental Results

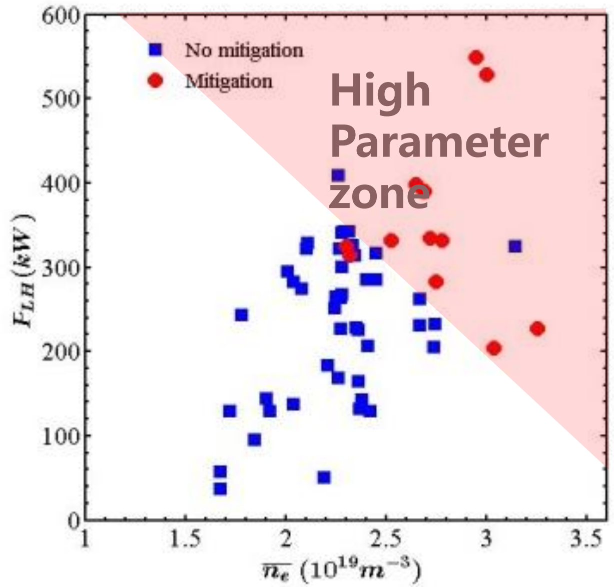
- ☐ ELM control with LHCD
- ☐ ELM control with impurity seeding

ELMs control with LHCD on HL-2A -Experimental observations



G.L. Xiao P.o.P., 2017





ELM and heat load Control

☐ ELM mitigation is clearly observed: f_{ELM} ↑ and A_{ELM} ↓

☐ No significant degradation of stored energy W_E .

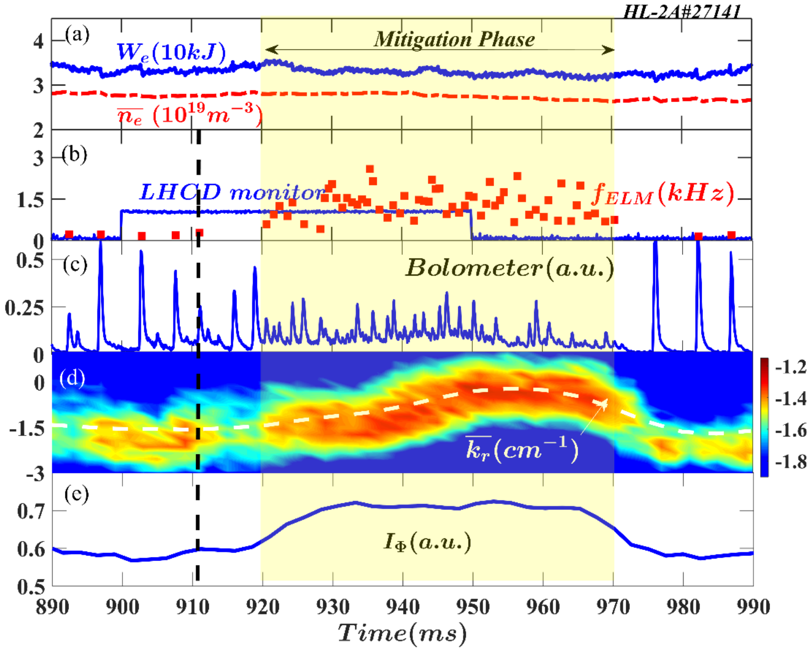
☐ Significant reduction of divertor peak heat load.

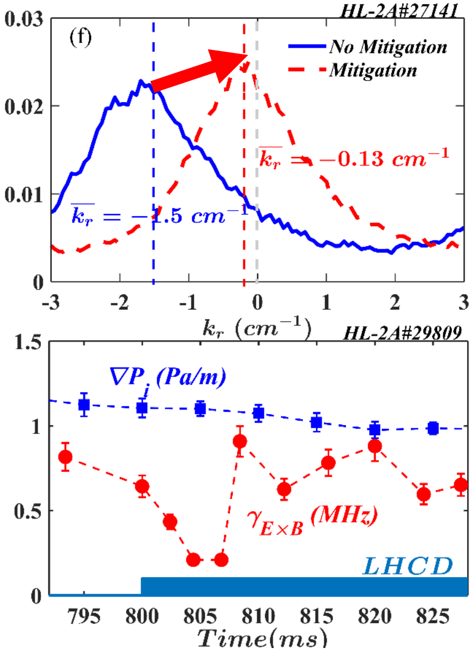
Parameter dependence

☐ Dependence in $\overline{n_e}$ and P_{LH} of the ELM mitigation with LHCD.

☐ Better chance to achieve mitigation with higher power and higher density ($n_e \geq 2.5 \times 10^{19}\ m^{-3}$, $P_{LHCD} \geq 300kW$).

ELMs control with LHCD on HL-2A -Role of Pedestal Turbulence

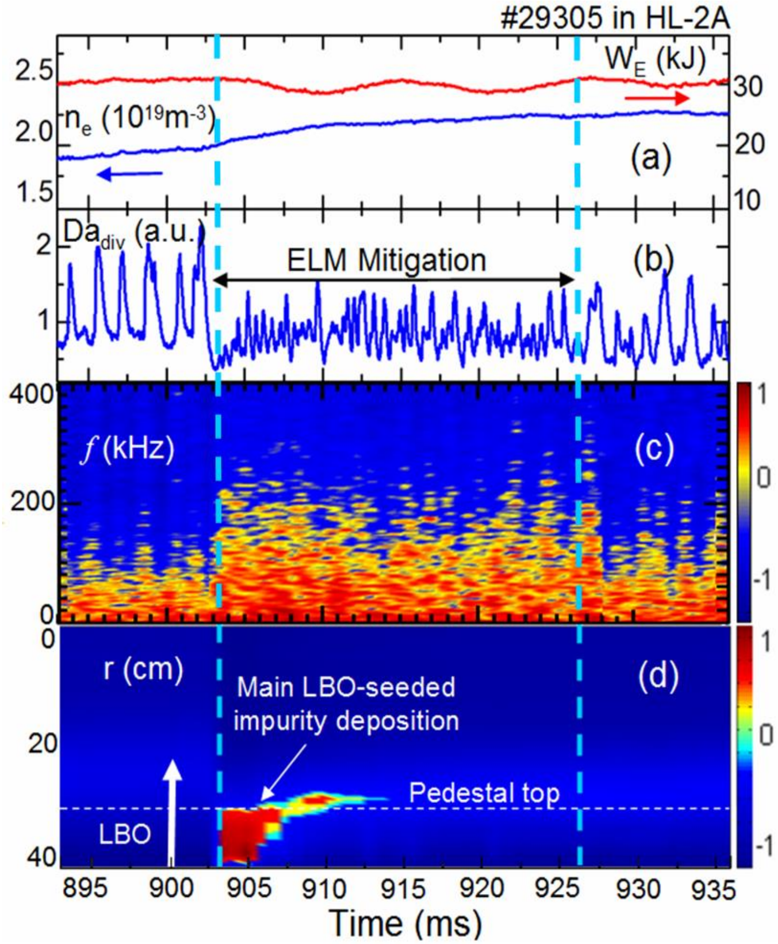


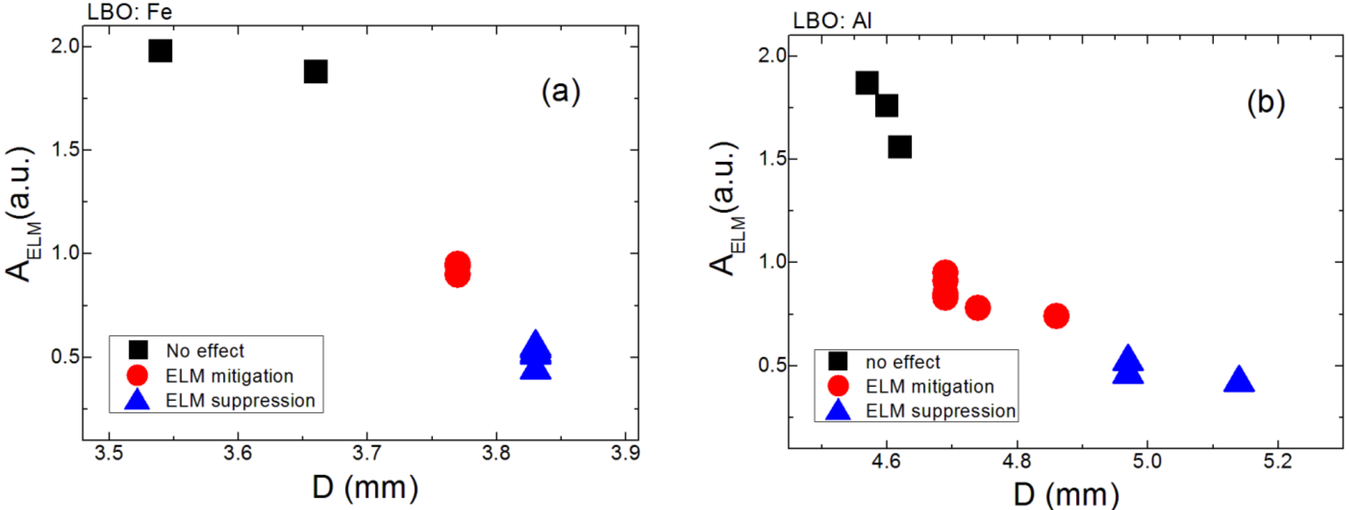


Turbulence regulation

- ☐ **Synchronization and desynchronization:** LHCD>0→a time interval→ ELM mitigation and pedestal turbulence enhancement.
- ☐ **Turbulence enhancement:** closely related to the turbulence k_r-spectrum shift.
- ☐ **k_r-spectrum shift:** $\overline{k_r} \approx -1.5\, cm^{-1} \rightarrow \overline{k_r} \approx 0\, cm^{-1}$
- ☐ **Velocity shear:** LHCD>0 → $\gamma_{E\times B}$ drops sharply.

ELMs control with impurity seeding -Experimental observations





ELM amplitude

Quantity of impurity

Y.P.Zhang N.F. 2018

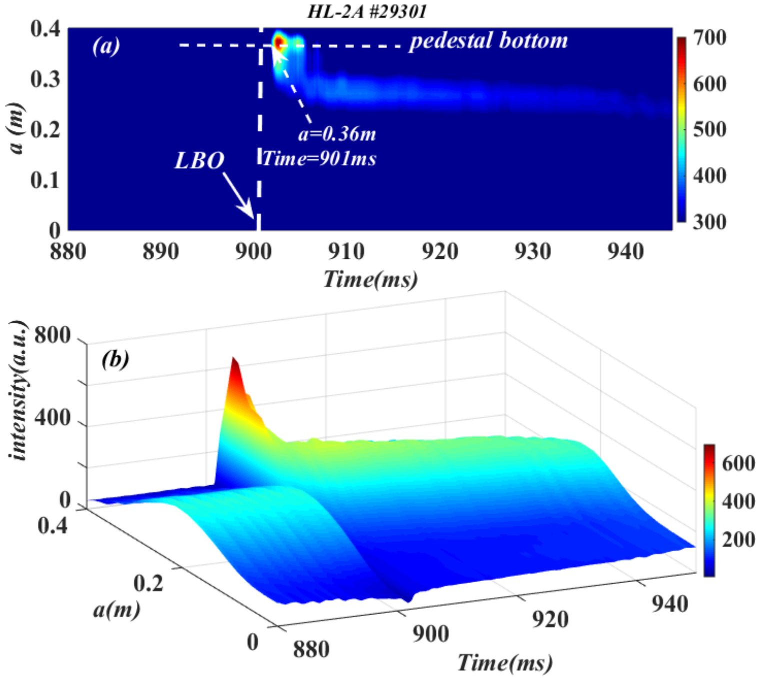
Experimental Observation

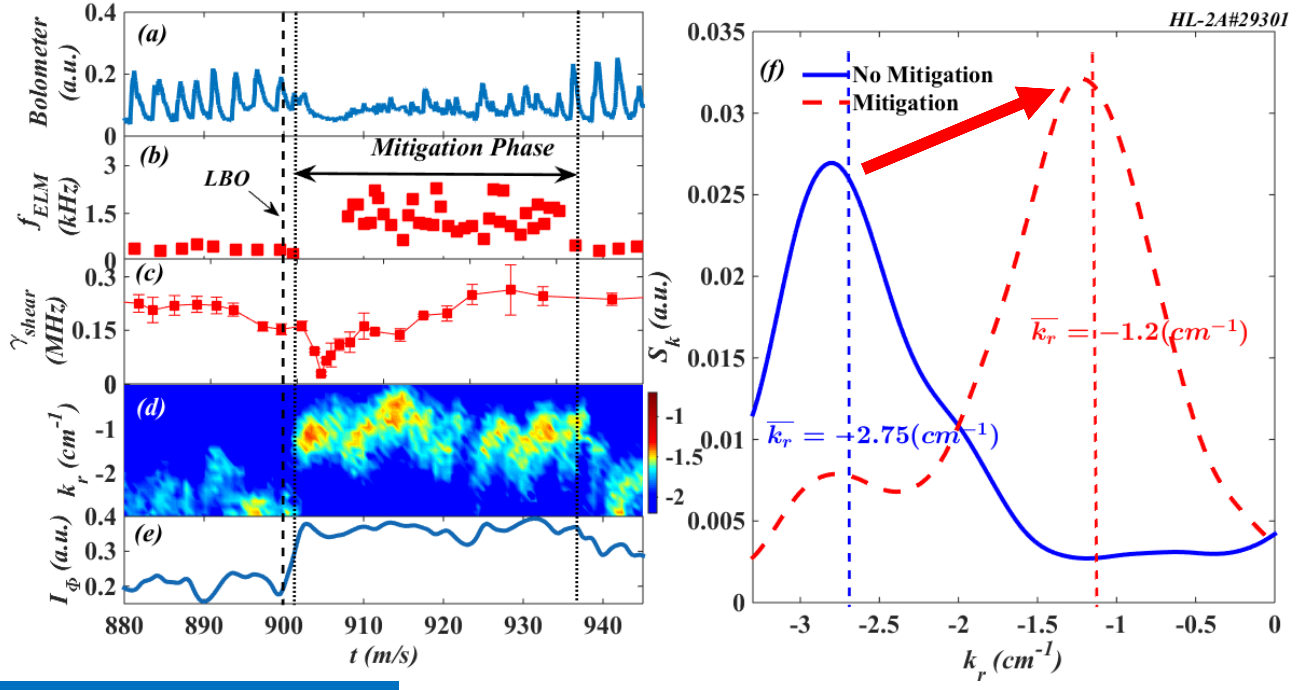
- ☐ **Location:** The impurity mainly in pedestal area.
- ☐ ELMs mitigation by impurity seeding with the enhancement of turbulence spectrum.

Parameter Dependence

- ☐ **The efficiency:** dependence on the quantity of electron injected with seeded impurity, or Z_{eff} of the impurity.

ELMs control with impurity seeding -Similarity on Pedestal Turbulence





Laser Blow-off(LBO) Fe impurity seeding

☐ **E×B Velocity shear**: Severe reduction after LBO.

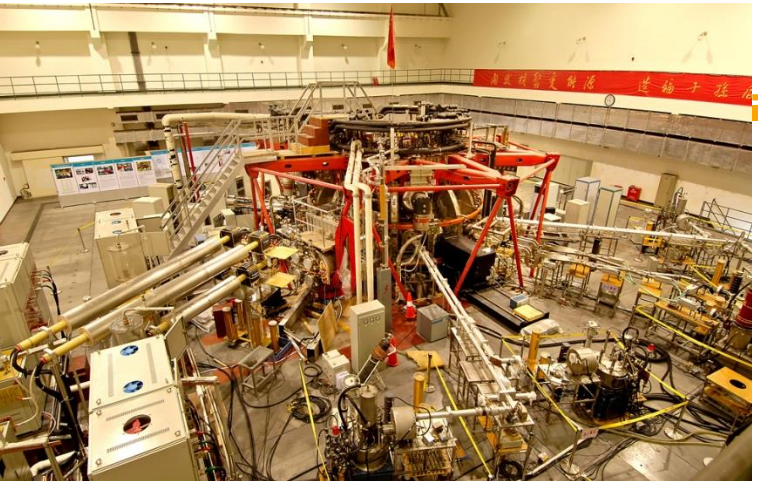
↓

☐ **Pedestal turbulence**: Intensity enhanced.

radial wavenumber spectral shift.

↓

☐ **ELM Mitigation**



Ⅲ. Theoretical Simulation

- ☐ Spectral shift model
- ☐ Typical simulation result
- ☐ Identification of critical growth rate γ_0
- ☐ Comparison

Spectral Shift Model

Model is based on the regulation of the turbulence amplitude by its radial wavenumber spectral shift caused by external velocity shear:

Linear growth rate

Velocity shear induced convection term

Diffusion in k_x space

$$\partial\phi/\partial t = \gamma_{k_y}\phi + \gamma_{E\times B}k_y\partial\phi/\partial k_x - \left(c_y k_y^2 + c_x k_x^2\right)\phi^2 + D(\partial^2\phi)/(\partial k_x^2) \qquad (1)$$

k_x: radial;
k_y: poloidal.

Dissipation term

$$\partial|\nabla p|/\partial t = Q - (\chi + \chi_0)|\nabla P| \qquad (2)$$

$$\gamma_{E\times B} = \alpha|\nabla P| + U_0 - \boldsymbol{U} \qquad (3)$$

(1) Nonlinear evolution of turbulence amplitude.

(2) Thermal transport equation.

(3) Velocity shear equation

U: Reduction value of the $\boldsymbol{\gamma_{E\times B}}$ from the external source input.

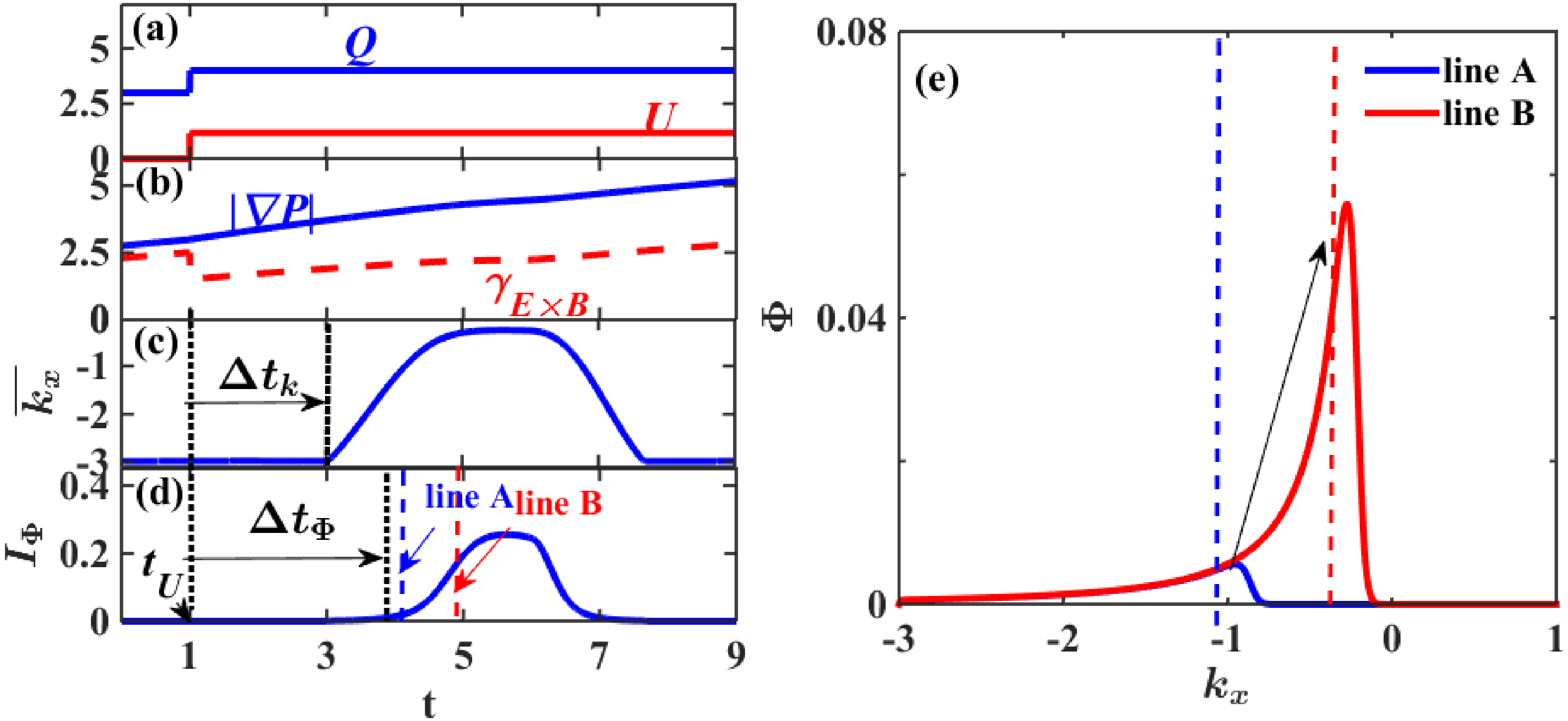
Typical Simulation Result

Q: heat source

U: reduction value of velocity shear

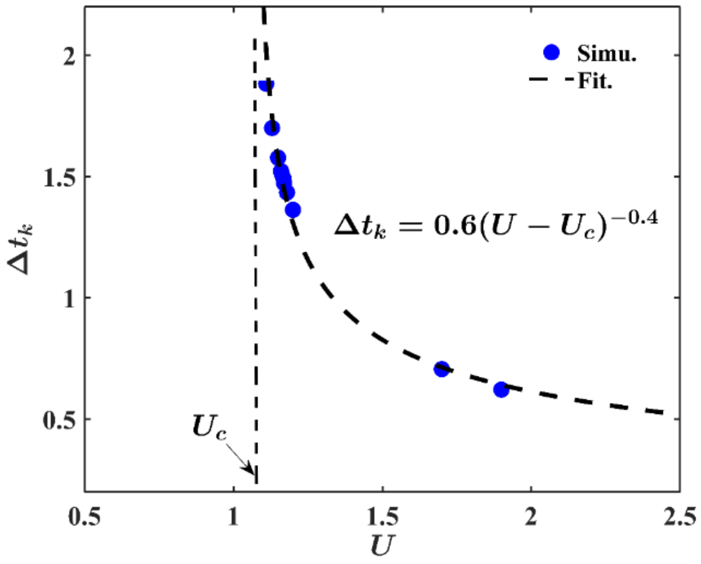
$\overline{k_x}$:Averaged Radial wavenumber

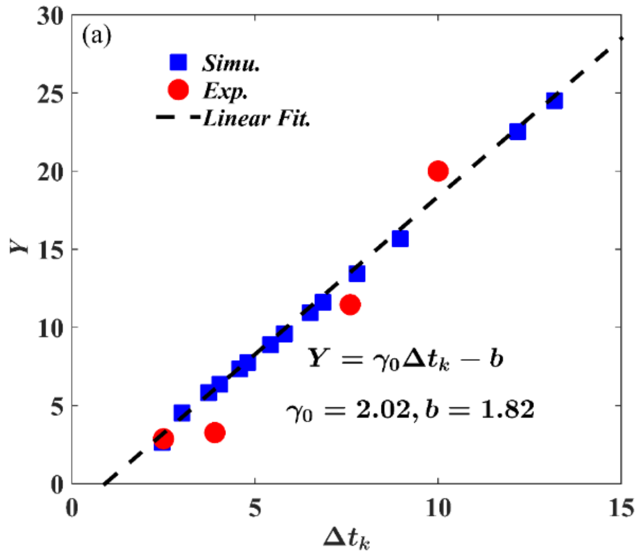
$I_{\boldsymbol{\Phi}}$:Turbulence intensity

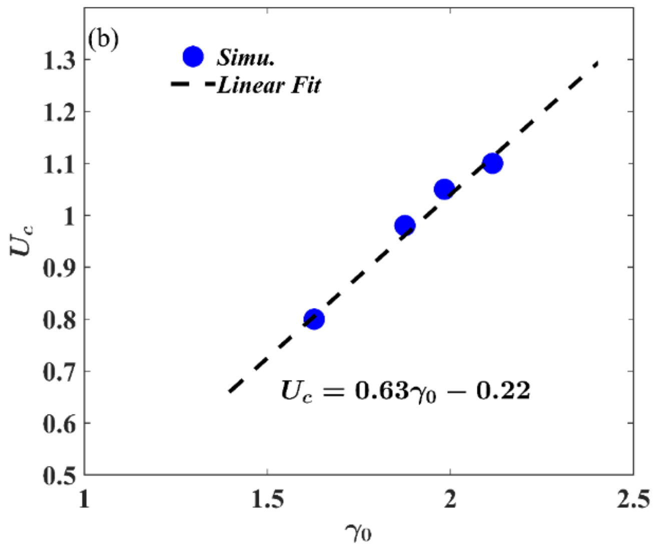


- ☐ U>0, $\gamma_{E\times B}$ drops sharply.
- ☐ Time delay: $U>0$, $\overline{k_x}\rightarrow\mathbf{0}$ with a time delay Δt_k, then turbulence intensity $I_{\boldsymbol{\Phi}}$ ↑.
- ☐ Turbulence enhancement: turbulence spectral shift $\overline{\boldsymbol{k_x}}\rightarrow\mathbf{0}$, the turbulence dissipation term$(\sim\boldsymbol{k_x^2})$ ↓, pedestal turbulence intensity $\boldsymbol{I_{\Phi}}$ ↑.

Identification of Critical Growth Rate γ_0





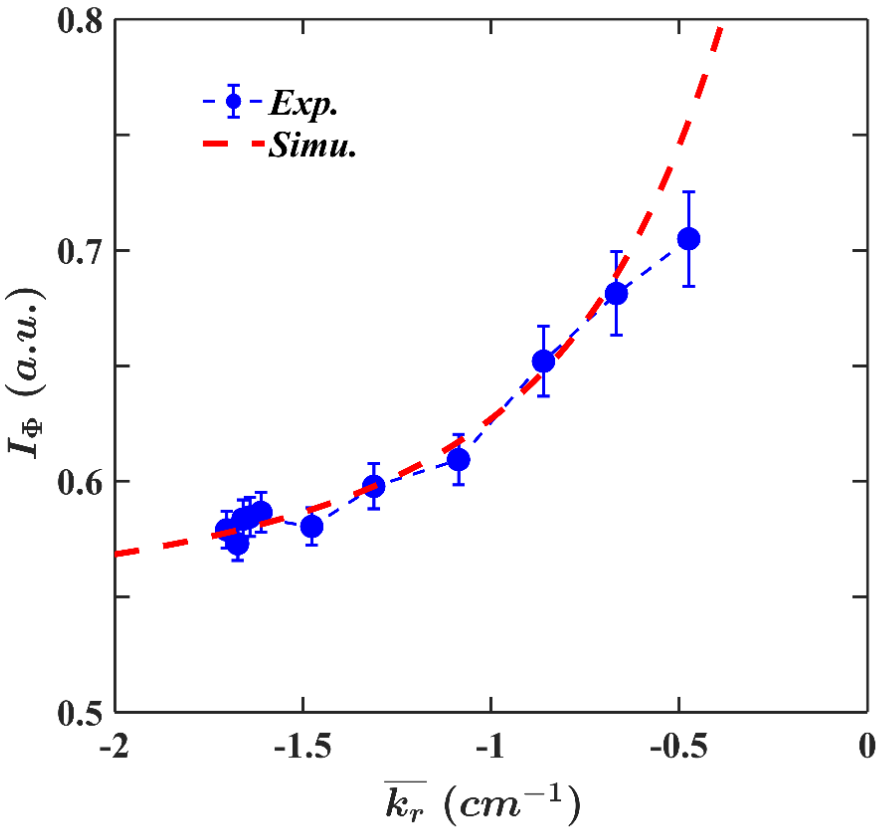


- ☐ **critical value U_c**: $U < U_c$ no effect on turbulence.

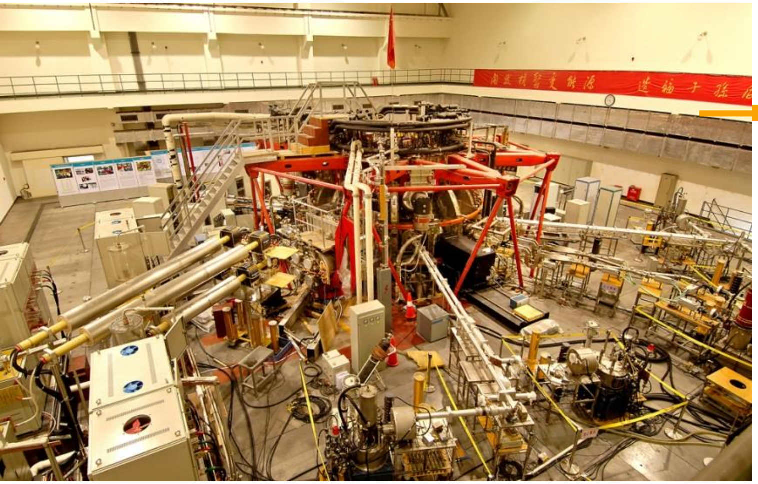
  $U > U_c$ triggering the variation of turbulence.

- ☐ **Identification of γ_0**: $Y = \int_0^{\Delta t_k} \gamma_{E\times B} dt \propto \Delta t_k$, $Y = \gamma_0 \Delta t_k - b$.
- ☐ Linear relation between γ_0 and U_c.
- ☐ **Role of γ_0**: key role for regulation of the turbulence amplitude by the radial wavenumber shift.

Comparison



- ☐ The radial wavenumber $k_x \to 0$, the turbulence dissipation term($\sim k_x^2$) ↓, pedestal turbulence intensity $\boldsymbol{I_\Phi}$ ↑.
- ☐ Good agreement on turbulence behavior between experimental and simulation result.



Ⅳ. Summary

- □ Mitigation effect
- □ Turbulence behavior
- □ Theoretical modeling

Summary

1 Mitigation Effect

- ELM mitigation with LHCD and impurity seeding is successfully achieved.
- Parameter dependence: LHCD($\boldsymbol{n_e \geq 2.5 \times 10^{19}\, m^{-3}, P_{LHCD} \geq 300kW}$)

  Impurity seeding: Z_{eff} of the impurity

2 Turbulence behavior

- LHCD/impurity seeding could reduce the plasma velocity shear.
- The close relation between pedestal turbulence enhancement and its radial wavenumber spectrum shifting to origin.

3 Theoretical modeling

- Theoretical model shows turbulence could be regulated by U_c or critical growth rate γ_0.
- Good agreement on turbulence regulation between experiment and theory.
- Plausible mechanism for ELM mitigation: External source input(such as LHCD and impurity seeding) → Edge velocity shear decrease → Turbulence radial spectral shift → Turbulence enhancement → ELM mitigation.

THANK YOU

for your attention!