Simulation study of the grassy ELM cycles within Edge Plasma Coupling Simulation framework

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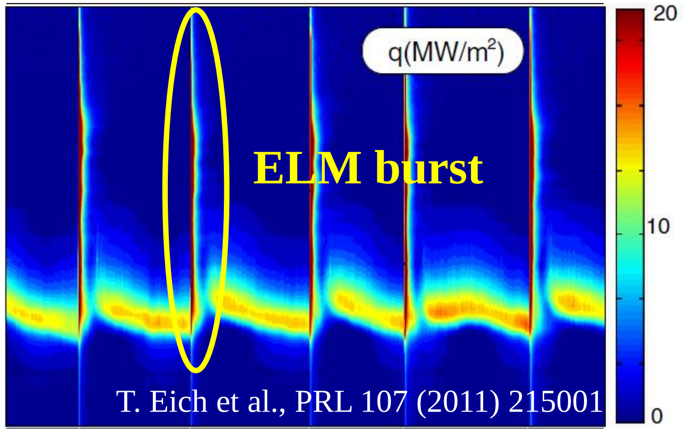
Fifth IAEA Technical Meeting on Divertor Concepts

Outline

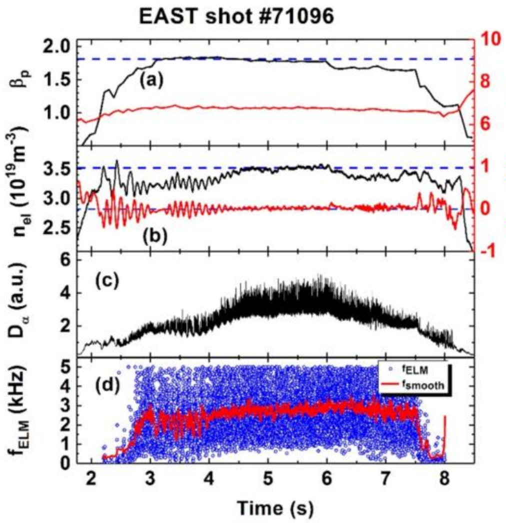
- Motivation
- Edge plasma coupling simulation framework (EPCS)
- Time-dependent simulation for grassy ELM cycles
- Impurity seeding: simultaneous detachment/ELM mitigation
- Conclusion

Motivation

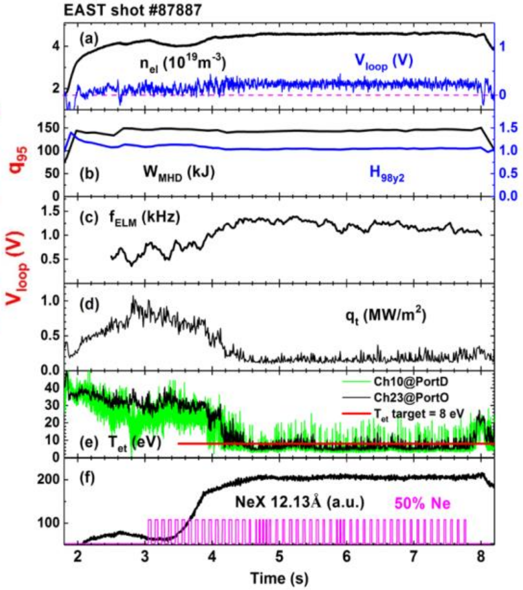
- Divertor is subjected to **huge heat load**, including both the **transient heat load due to ELMs** and **steady-state heat load** in between ELMs
- For fusion reactor, steady-state operation requires
  - **High confinement plasma – fusion gain**
  - **Small/no ELM – control the transient heat load**
  - **Detachment – reduce the (steady-state) heat load**
- On EAST tokamak (also AUG, JET, DIII-D…)
  - **High-performance grassy ELM regime** accessed
  - **Detachment and small ELM simultaneously** achieved by **impurity seeding**



T. Eich et al., PRL 107 (2011) 215001



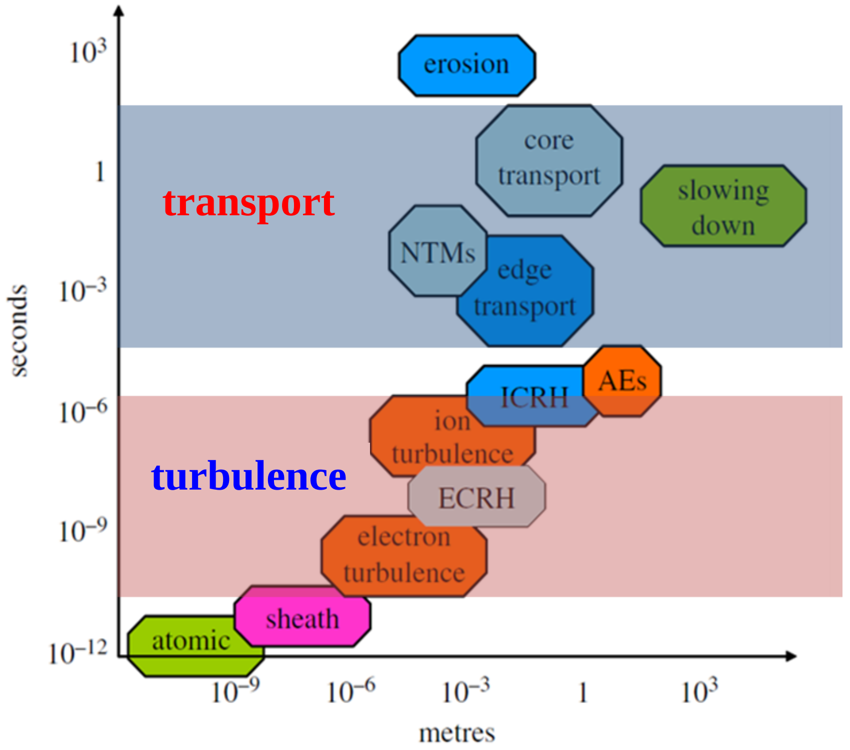
Q.Q. Yang et al., NF (2020)



G.S. Xu, et al., NF (2020)

Motivation

- To investigate the **physical mechanism**, **numerical simulation** is necessary
  - Also improve the ability of **predicting the edge plasma behavior** for future devices
- However, numerical simulation of **edge plasma evolution over multi-ELM cycles** is difficult due to **large gap between turbulence (10^{-7} s) and transport (10^{-2} s) time scales**



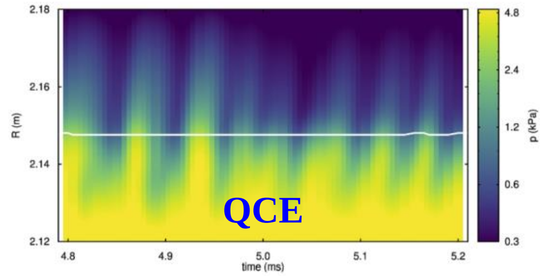
Transport codes	**SOLPS-ITER**、**EMC3-EIRENE**、**SOLEDGE2D-EIRENE**
Turbulence codes	**BOUT++**、**JOREK**、**GBS**、**SOLEDGE3X**、**GRILLIX**

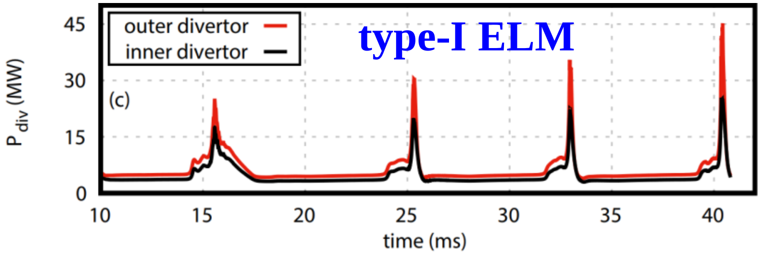
Motivation

computational complexity

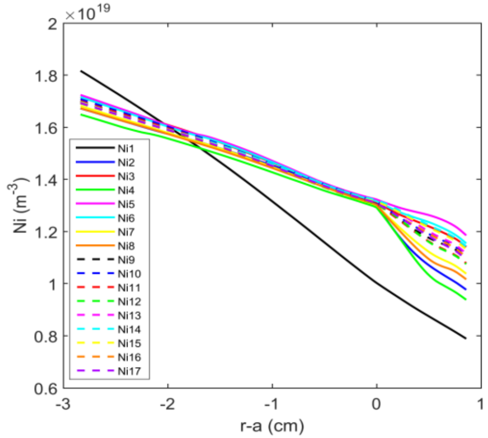
Turbulence simulation in a long-time scale	turbulence/transport coupling simulation	Include turbulent trans. coeff. in transport code
Need artificial source	Verified for steady-state simulation	Under development

A Cathey, et al. PPCF (2022), NF (2020) JOREK



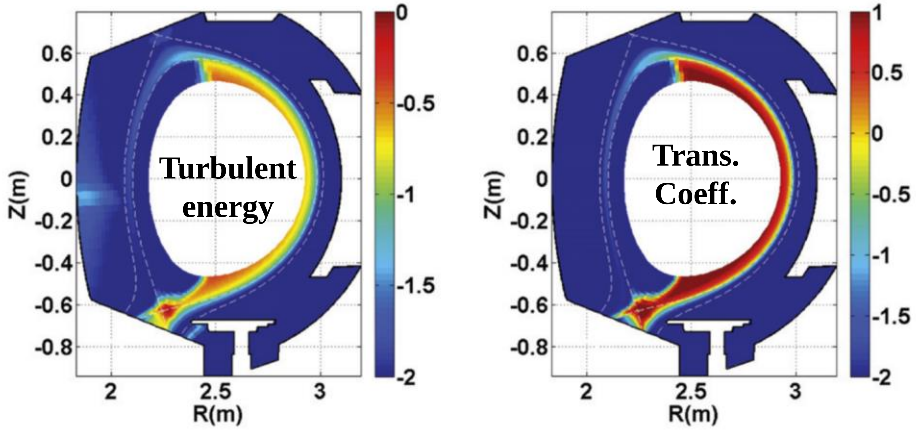


T. D. Rognlien, et al., JNM (2005) BOUT-UEDGE
D. R. Zhang et al., NF (2020) BOUT++-SOLPS



S. Baschetti, et al., NF (2021) SolEdge2D-EIRENE
W. Dekeyser, et al., CPP (2022) SOLPS-ITER

Reynolds Averaged Navier–Stokes (RANS)



Develop the multi-scale coupling simulation framework

- ✓ Automatic
- ✓ High accuracy
- ✓ High efficiency

Time-dependent simulation of edge plasma evolution over multi-ELM cycles

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EPCS framework

Liu et al. PPCF 67 (2025) 55004

■ **Edge plasma coupling simulation framework** is developed based on **Python**

GUI

PREPROCESS
*user configuration CONFIG
*generate parameters for INIT_TRANS, INIT_TURB, RUN_TRANS and RUN_TURB
*initialize the workflow

RUN_TURB
*write input parameters (IO)
*run turbulence code (Tools)
*read transport coefficients (IO & CALC)

RUN_TRANS
*write input parameters (IO)
*run turbulence code (Tools)
*read plasma profiles (IO & CALC)

INIT_TURB
*plasma profile interpolation (CALC)
*data check and fix (CALC)
*write data file (IO)

INIT_TRANS
*transport coefficient interpolation (CALC)
*data check and fix (CALC)
*write data file (IO)

TURB
*IO: file I/O (Tools)
*CALC: calculation and interpolation (Tools)
*PLOTTING: data visualization

TRANS
*IO: file I/O (Tools)
*CALC: calculation and interpolation (Tools)
*PLOTTING: data visualization

Tools
write file, read file, run code, interpolate, ……

Provide a friendly way for users to **configure the desired coupling simulation workflow** via GUI

Build workflows based on EPCS for specified purpose

- **Drivers** for the running of the turbulence/transport code
- Provide the **necessary data transfer interfaces** for the subsequent turbulence/transport simulations in the coupling simulation workflow

SOLPS/BOUT++

Provide necessary **interfaces for the native transport/turbulence codes**

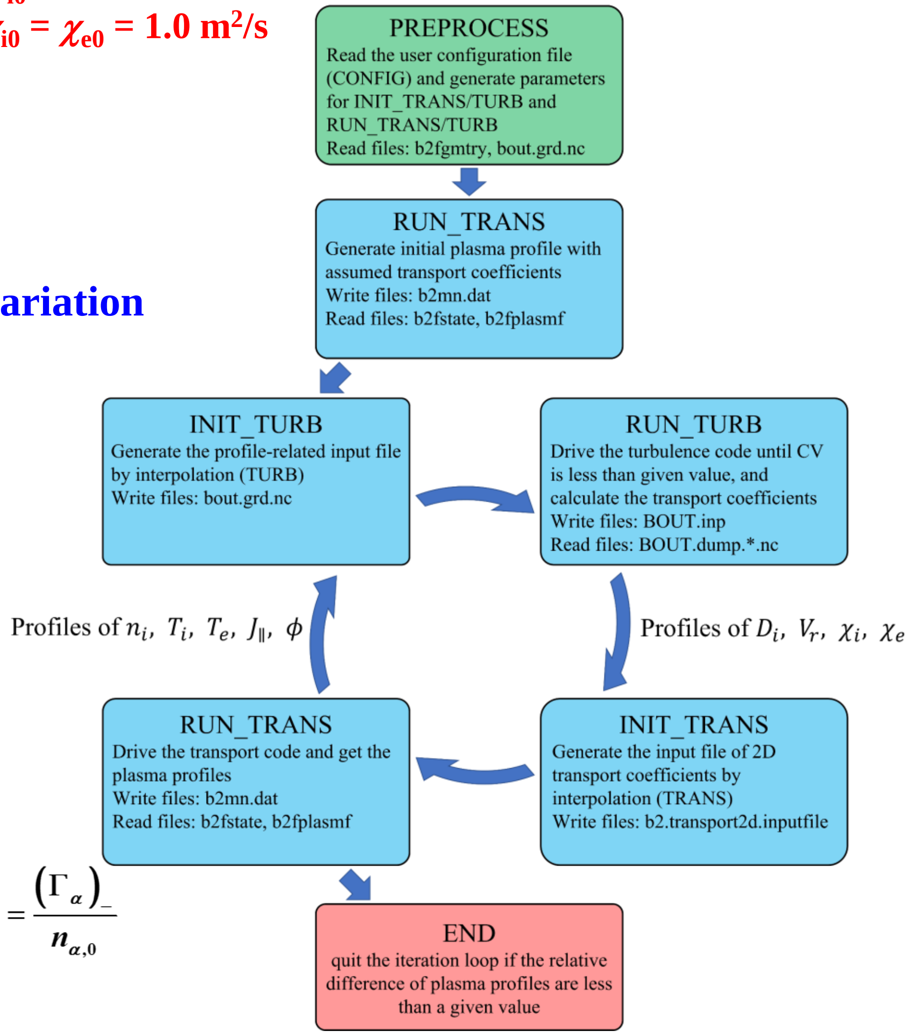
- **Bivariate spline interpolation in (ψ, θ) coordinate system**: **smoothness and accuracy**
- **Breadth-first search algorithm**: **efficiency**

Provide general and frequently-used **routines** for the components

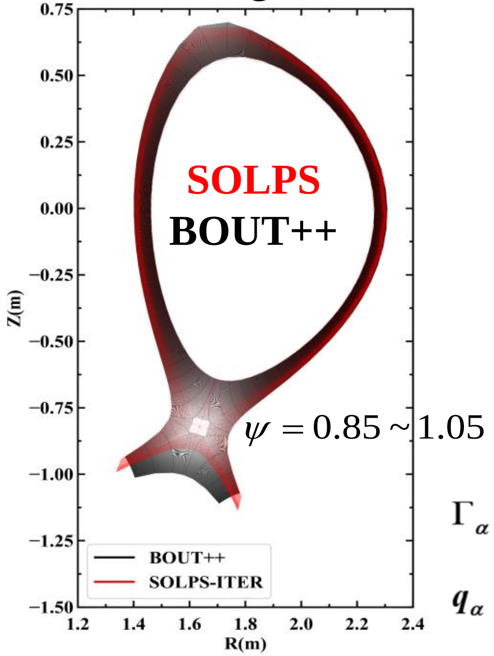
Steady-state coupling simulation workflow

- Initial profiles generated by SOLPS with assumed trans. coeff.
- Iteration between turbulence/transport codes until converges
- Test based on ELM-free stage during EAST H-mode discharge
- Speeding up the coupling simulation
  - Identify quasi-steady-state of turbulence simulation based on coefficient of variation

$D_{i0} = 0.5\ \mathrm{m^2/s}$
$\chi_{i0} = \chi_{e0} = 1.0\ \mathrm{m^2/s}$



EAST #56129@t = 5.55 s



SOLPS-ITER (36×64)
- **Include currents and drifts**
- **CEI: $n_i = 2.2 \times 10^{19}\ \mathrm{m^{-3}}$, $T_i/T_e = 450/320$ eV**
- **Evolving n_i, T_i, T_e, $J_\parallel$ and ϕ**

BOUT++ (200×64×64)
- Six-field two-fluid model
- $n = 0$ components fixed
- **Provide transport coefficients D_i, V_i and χ_i/χ_e**

$$\Gamma_\alpha = \boxed{\langle n_\alpha V_{E,1} \rangle} + \boxed{\langle n_\alpha V_{\parallel,\alpha} b_1 \rangle}$$

$$q_\alpha = \boxed{\frac{5}{2}\langle n_\alpha T_{\alpha,1} V_{E,1} \rangle} + \boxed{\frac{5}{2}\langle n_\alpha V_{\parallel\alpha} T_{\alpha,1} b_1 \rangle - \langle \kappa_{\parallel,\alpha} \nabla_\parallel T_\alpha b_1 \rangle}$$

$\boldsymbol{E}\times\boldsymbol{B}$ drift

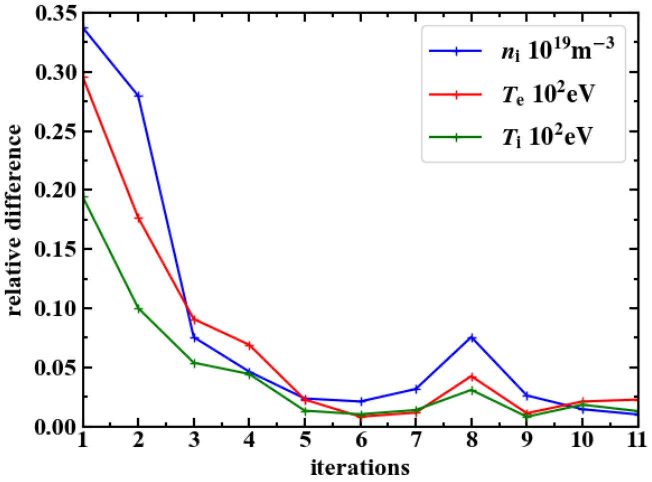
magnetic fluttering

$$D_\alpha = -\frac{(\Gamma_\alpha)_+}{\partial_r n_{\alpha,0}} \qquad V_\alpha = \frac{(\Gamma_\alpha)_-}{n_{\alpha,0}}$$

$$\chi_\alpha = -\frac{q_\alpha}{n_{\alpha,0}\partial_r T_{\alpha,0}}$$

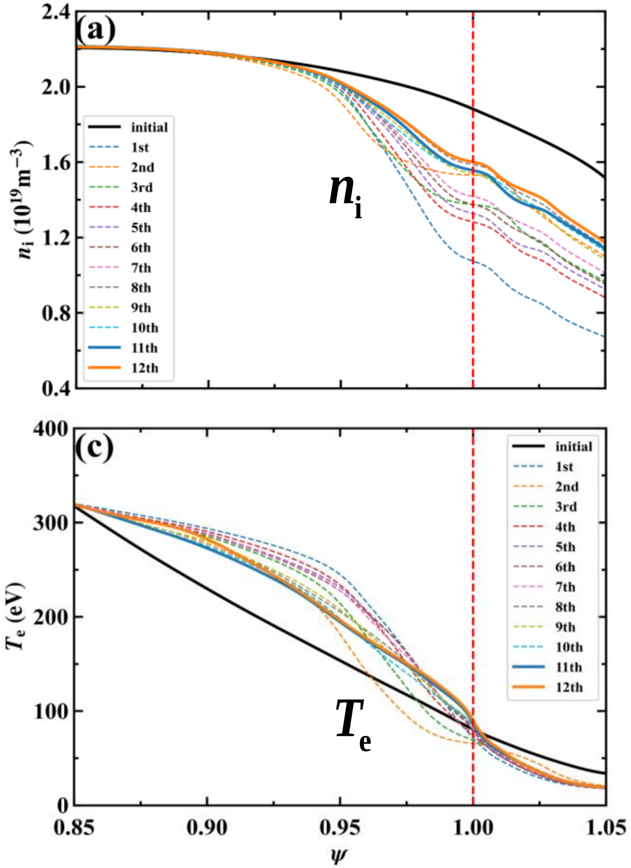
Steady-state coupling simulation workflow

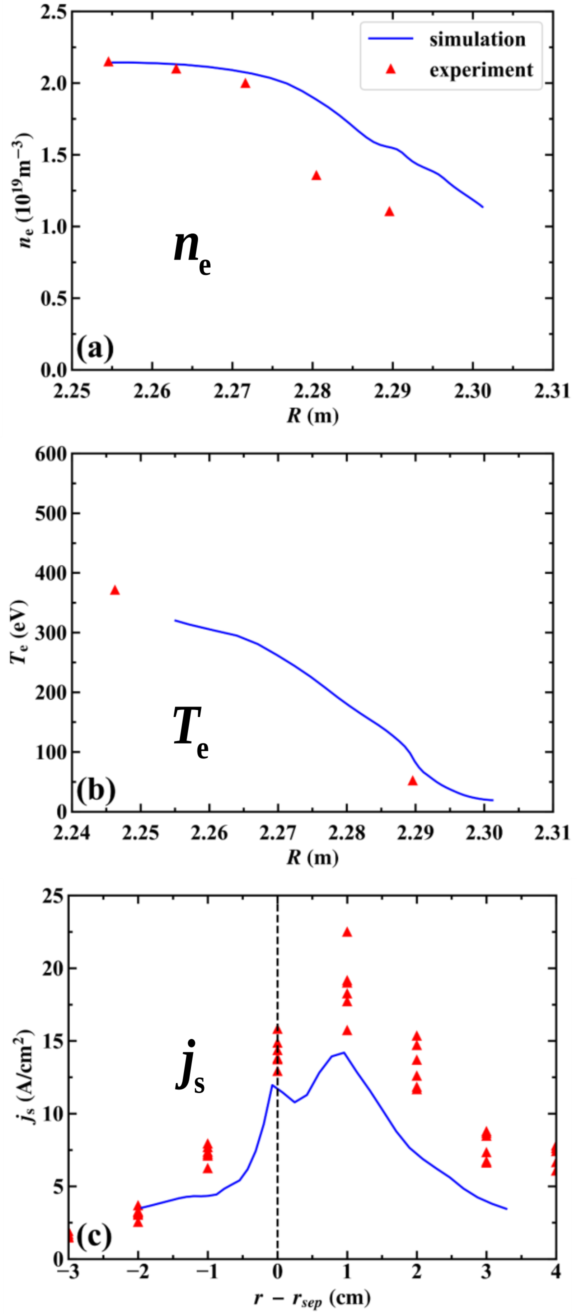
- As expected, plasma profiles converge along with iterations
- Profiles at OMP and target in good agreement with experiment



Relative differences of plasma profiles between m and m-1 iteration

$$diff\left(PP^m\right) \equiv \frac{\sum_{i=0}^{N_x-1}\sum_{j=0}^{N_y-1}\left|PP_{i,j}^m - PP_{i,j}^{m-1}\right|}{\sum_{i=0}^{N_x-1}\sum_{j=0}^{N_y-1}\left|PP_{i,j}^m\right|}$$





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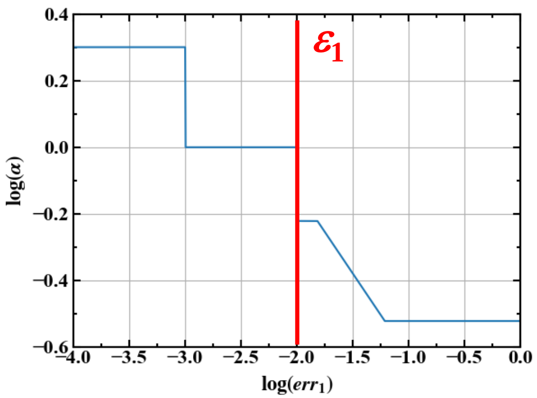
Time-dependent coupling simulation workflow

- **Loop1: inner iteration**
  - ✓ Ensure the **self-consistence** between the evolution of plasma profiles and the turbulence transport flux based on the **predictor-corrector method**
- **Loop2: adaptive change of time step**
  - ✓ **ELM burst**: decrease time step size to ensure accuracy
  - ✓ **Recovery**: increase time step size to improve efficiency

change ratio of the time step size

$$\Delta t^i_{0,\mathrm{new}} = \left(\frac{\varepsilon_1}{err_1}\right)^{\frac{1}{k+1}} \Delta t^i_{0,\mathrm{old}} = \boxed{\alpha\left(err_1\right)} \Delta t^i_{0,\mathrm{old}}.$$

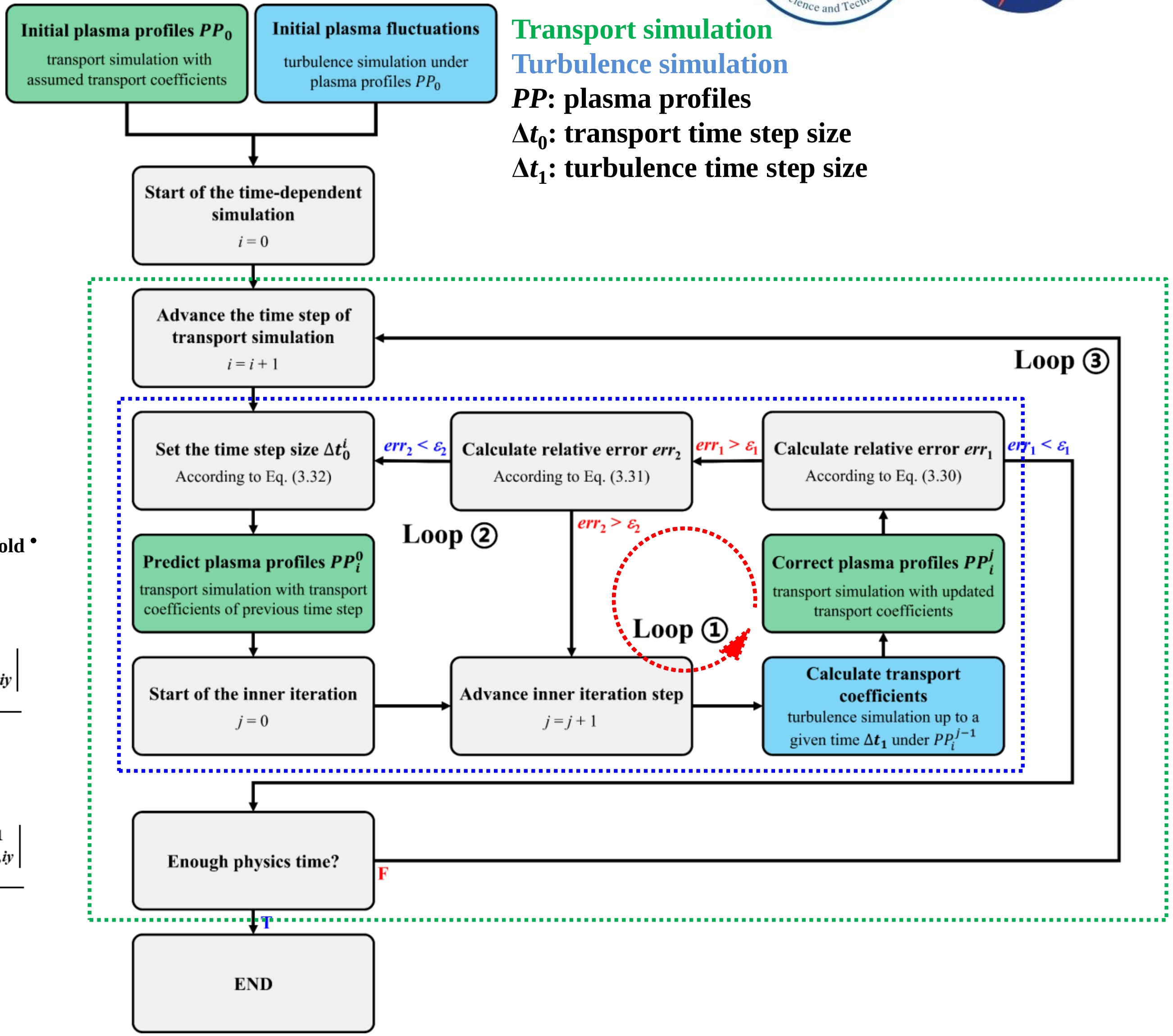


Relative error

$$err_1\left(PP^j_i\right) = \frac{\sum_{ix=0}^{nx-1}\sum_{iy=0}^{ny-1}\left|PP^j_{i,ix,iy} - PP^0_{i,ix,iy}\right|}{\sum_{ix=0}^{nx-1}\sum_{iy=0}^{ny-1} PP^j_{i,ix,iy}}$$

$$err_2\left(PP^j_i\right) \equiv \frac{\sum_{ix=0}^{nx-1}\sum_{iy=0}^{ny-1}\left|PP^j_{i,ix,iy} - PP^{j-1}_{i,ix,iy}\right|}{\sum_{ix=0}^{nx-1}\sum_{iy=0}^{ny-1} PP^j_{i,ix,iy}}$$

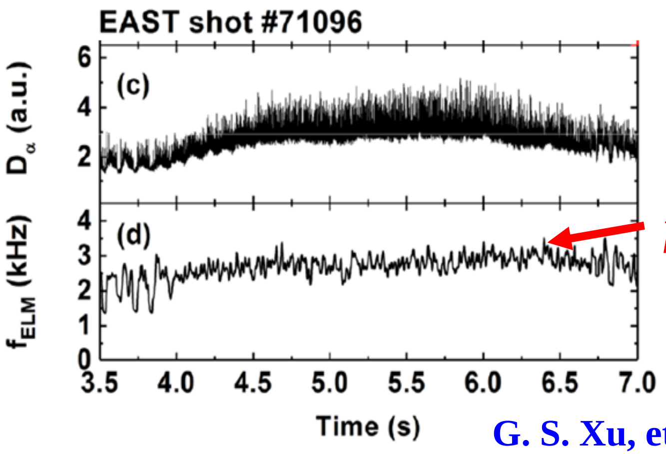
- **Loop3: advance physics time step**



Transport simulation
Turbulence simulation
PP: plasma profiles
Δt_0: transport time step size
Δt_1: turbulence time step size

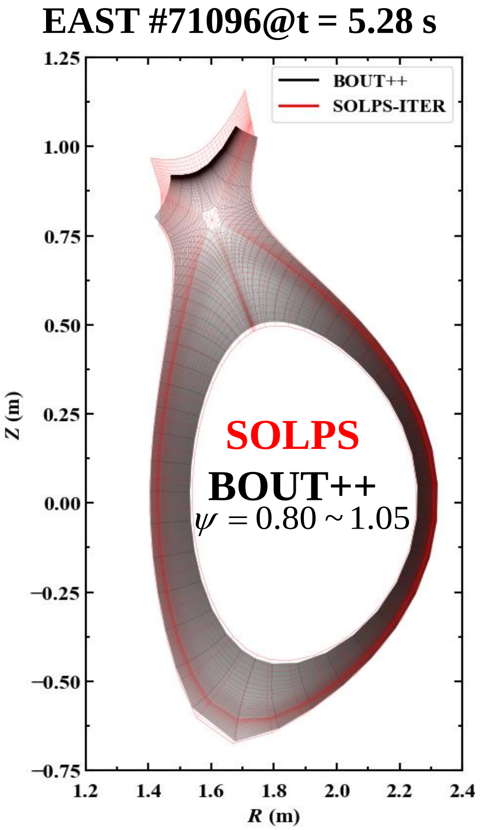
Simulation setup

- Based on **EAST grassy ELM experiment** (#71096)
  - **SOLPS-ITER (36×64)**
    - CEI: $n_i = 1.5 \times 10^{19}$ m^{-3}, $P_{SOL} = 1.6$ MW
    - Include currents and drifts, time-dependent
    - **Δt_0: adaptive ($\Delta t_{SOLPS} = 1 \times 10^{-6}$ s)**
    - **Evolving n_i , T_i , T_e, $J_\parallel$ and ϕ**
  - **BOUT++ (200×64×64)**
    - Six-field two-fluid model, n = 0 components fixed
    - **$\Delta t_1 = 20\ \tau_A$ ($\Delta t_{BOUT++} = 1\ \tau_A$)**
    - **Provide transport coefficients D_i , V_i and χ_i/χ_e**

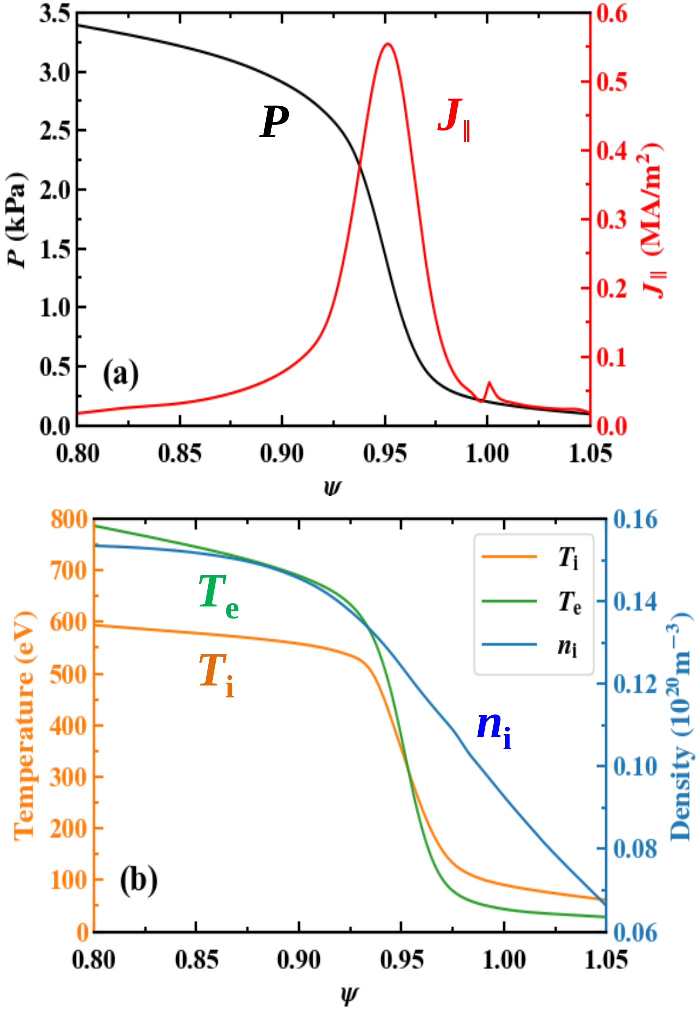


$f_{ELM} \approx$ 2kHz

G. S. Xu, et al., PRL (2019)

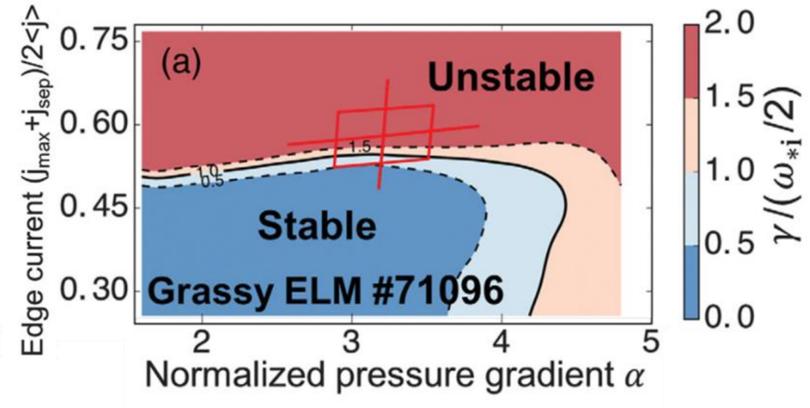


Initial profiles

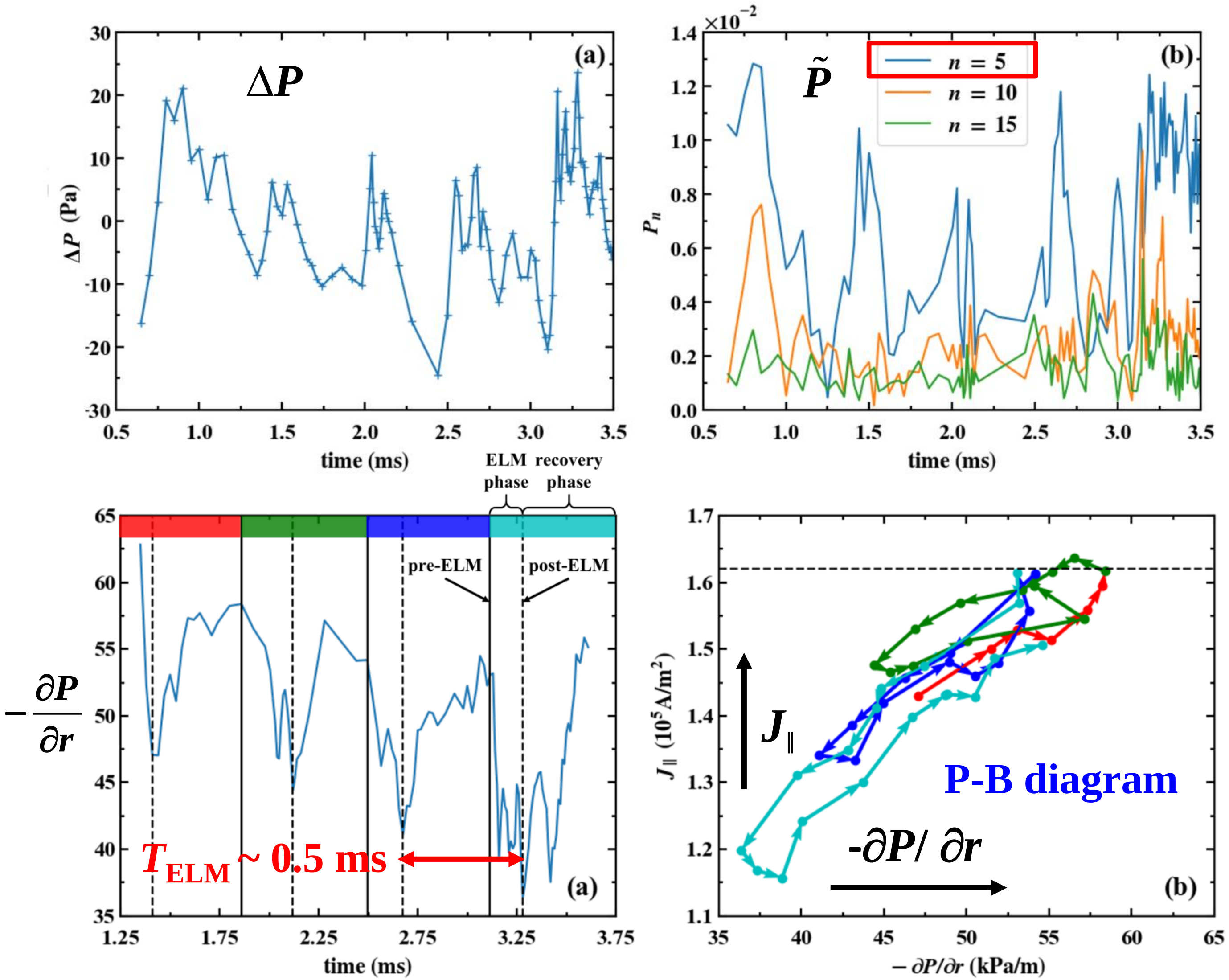


ELM cycles

- Quasi-periodical rise and fall of pressure appears at **pedestal foot ($\psi \approx 0.98 \sim 1.00$)**
- **ELM frequency ~ 2 kHz** – consistent with experiment
- **Counter-clockwise trajectory** on the P-B diagram
  - Cross the **peeling boundary**
  - In agreement with the **linear simulation**

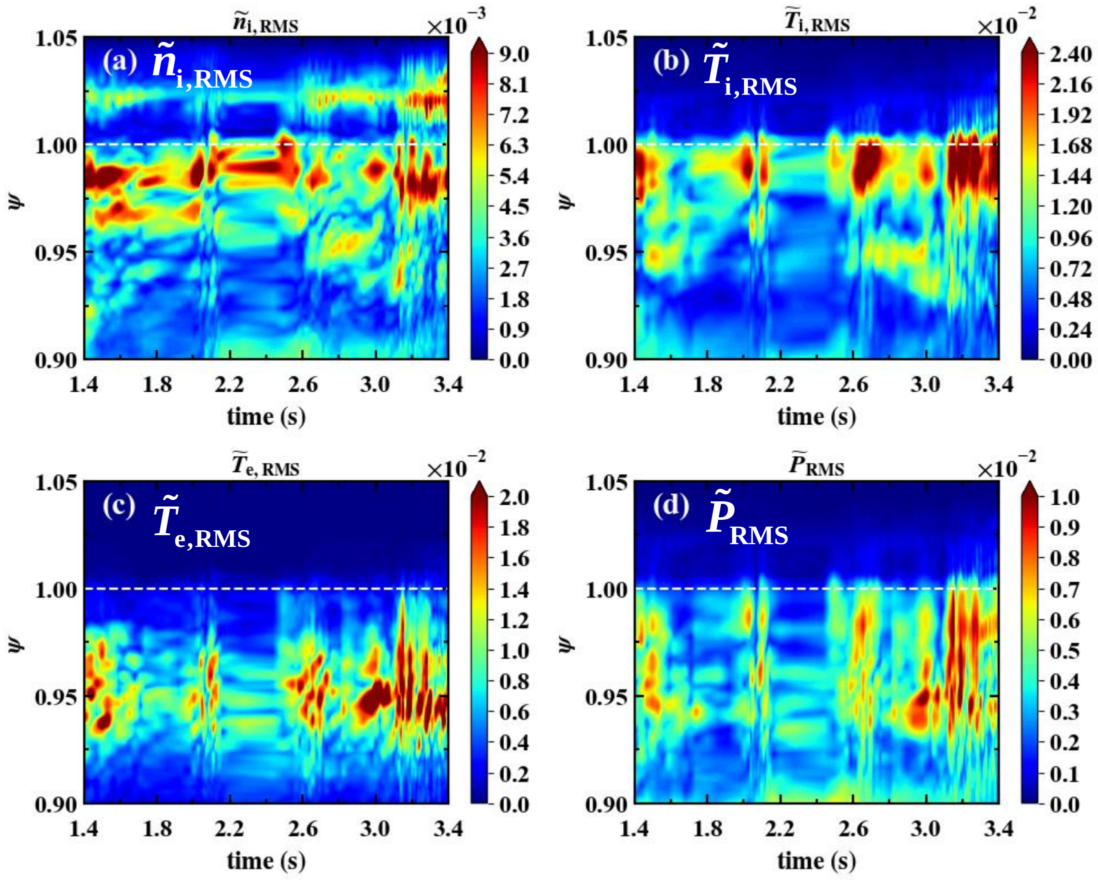


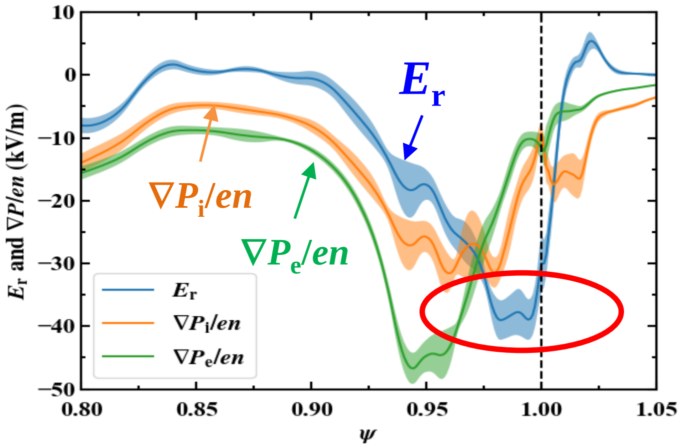
G. S. Xu, et al., PRL (2019)



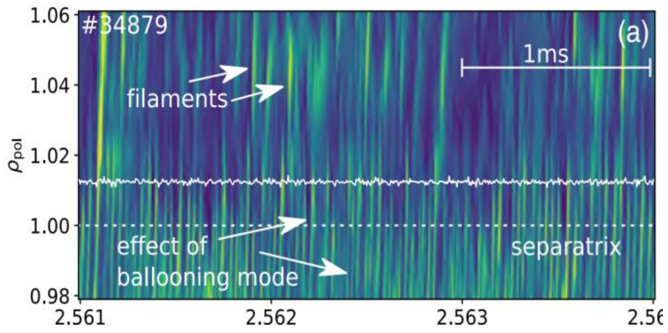
Radial distribution of fluctuations

- Density and ion temperature fluctuations locate at **pedestal foot** ($\psi \approx 0.99$)
- Electron temperature fluctuations locates at **gradient region** ($\psi \approx 0.95$)





Similar simulated E_r profile reported on FEC2025



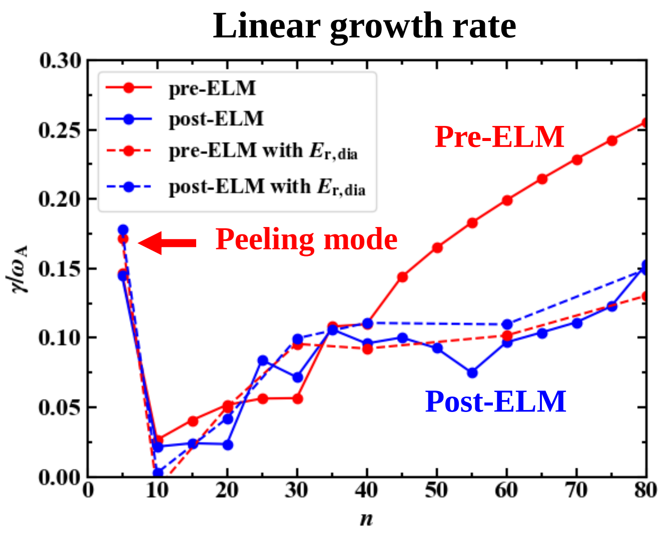
QCE on AUG

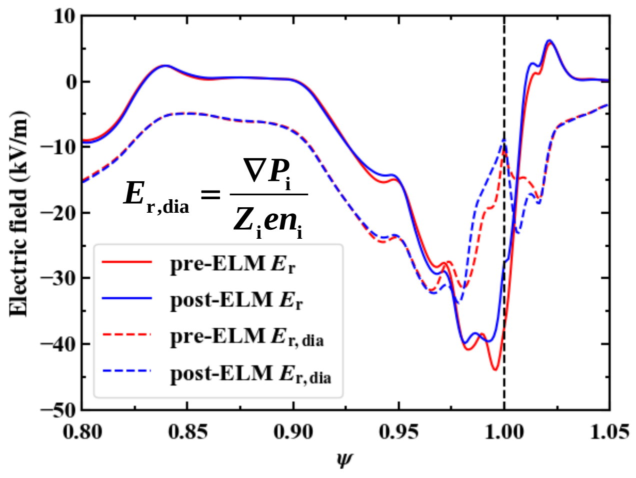
Ballooning mode

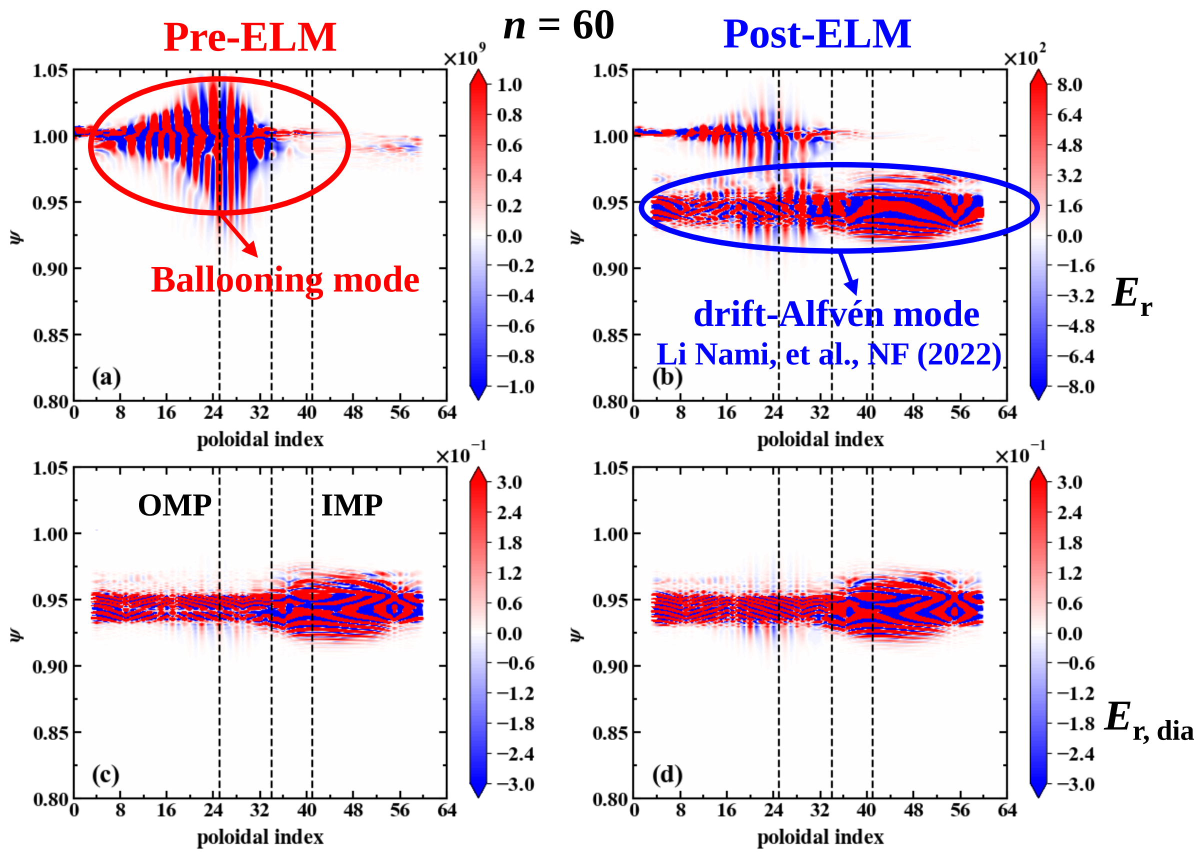
G. F. Harrer, et al., PRL (2022)

Physical mechanism: linear growth rate

- Comparing linear growth rate under profiles **pre-** and **post-ELM**
  - ***n* = 5 peeling mode** most unstable (agree with the analysis in **G. S. Xu, et al., PRL (2019)**)
  - **Periodical change** for **high *n* ballooning modes (50-80)** with **simulated E_r**







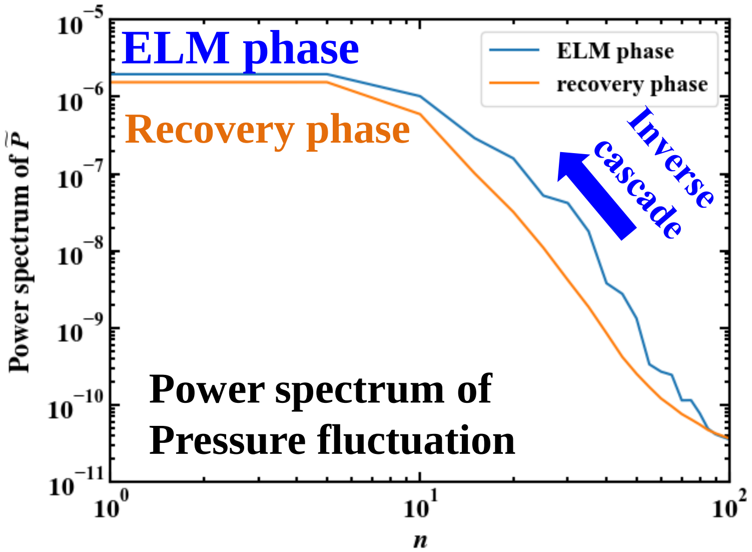
Physical mechanism: nonlinear interaction

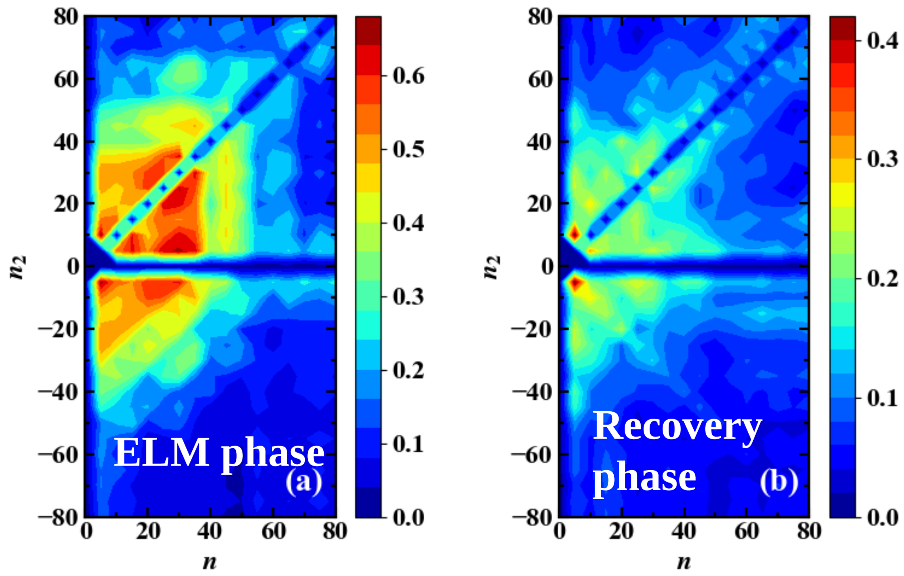
- However, while the linear growth rate almost unaffected, strength of **n = 5 mode periodically evolves**
- The strength of **nonlinear interaction between low and high n modes**:
  - Amplitude of low n mode increases in ELM phase
  - Strong interaction during ELM phase

→ **Low n mode driven by nonlinear interaction: inverse cascade**

$$\frac{\partial}{\partial t}P_n(t)=\underbrace{\boxed{\gamma_n}}_{\text{Linear growth}}P_n(t)+\sum_{\substack{n_1\geq n_2,\\ n_1+n_2=n}}\underbrace{\boxed{\Lambda_n}}_{\text{Nonlinear interaction}}(n_1,n_2)P_{n_1}(t)P_{n_2}(t)+\text{dissipation},$$

Ch. Ritz, et al., Phys. Fluids (1989)
S. Chai, Y. Xu*, et al., PoP (2017)





bispectrum

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

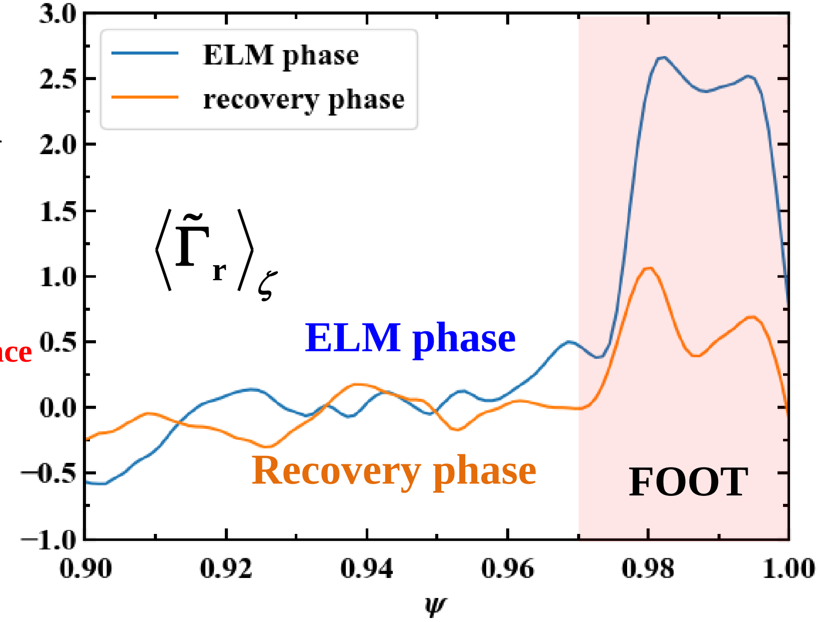
$$\hat{B}_{XYZ}(n_1,n_2)=X(n_1)Y(n_2)Z^*(n_1+n_2)$$

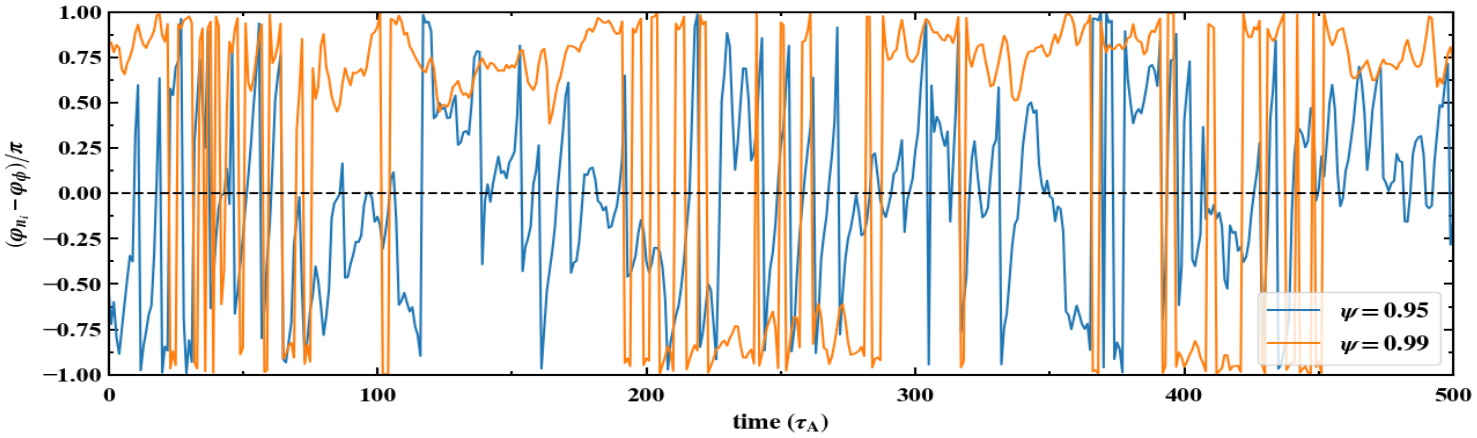
Radial particle transport

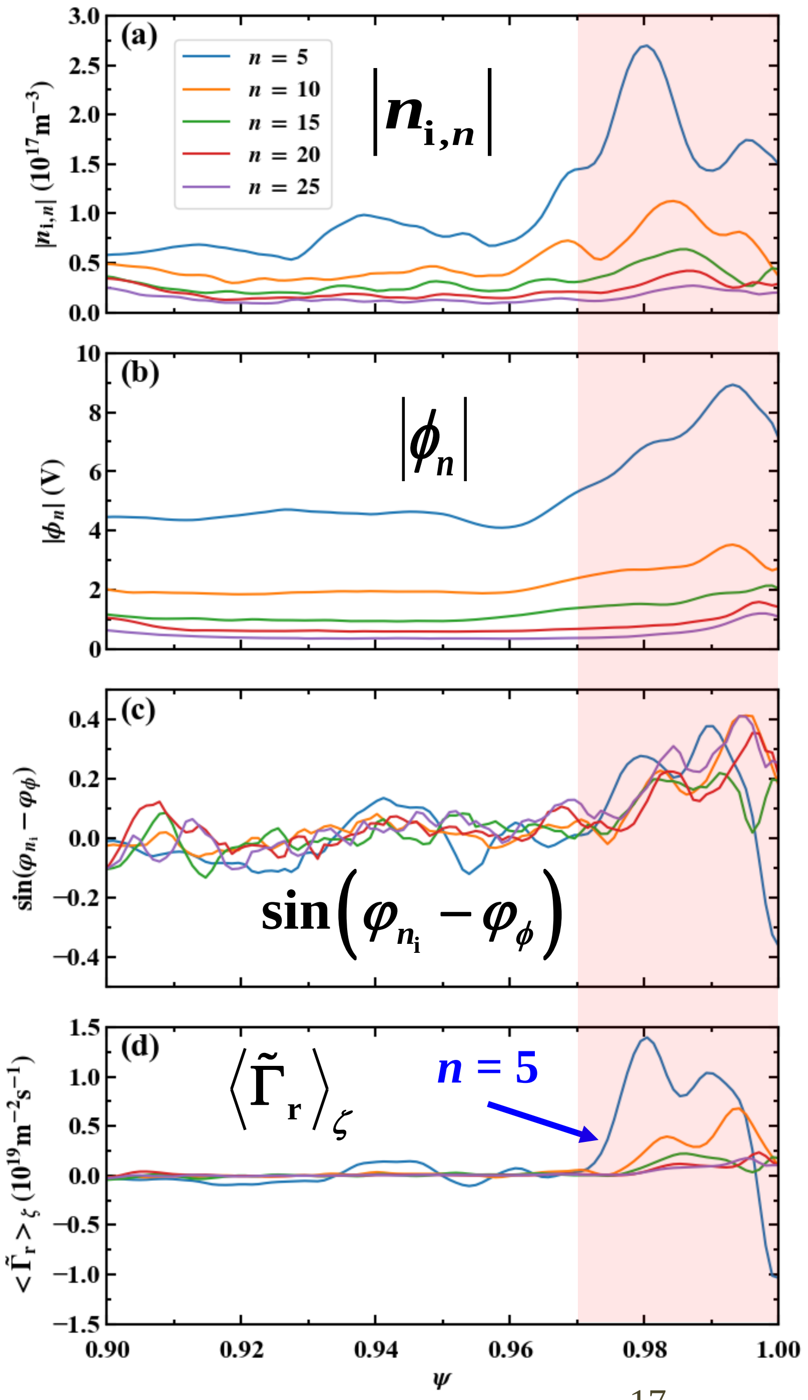
- **Dominated by n = 5 mode**
- **Strong particle transport at pedestal foot: important for maintaining low density gradient**

Radial particle flux **density fluc.** **Potential fluc.** **Phase difference**

$$\left\langle \tilde{\Gamma}_{\mathrm{r}} \right\rangle_{\zeta} \approx \frac{2}{RB_{\mathrm{p}}} \sum_{n>0} n \boxed{\left|n_{\mathrm{i},n}\right|} \boxed{\left|\phi_n\right|} \sin\boxed{\left(\varphi_{n_{\mathrm{i}}} - \varphi_{\phi}\right)}.$$

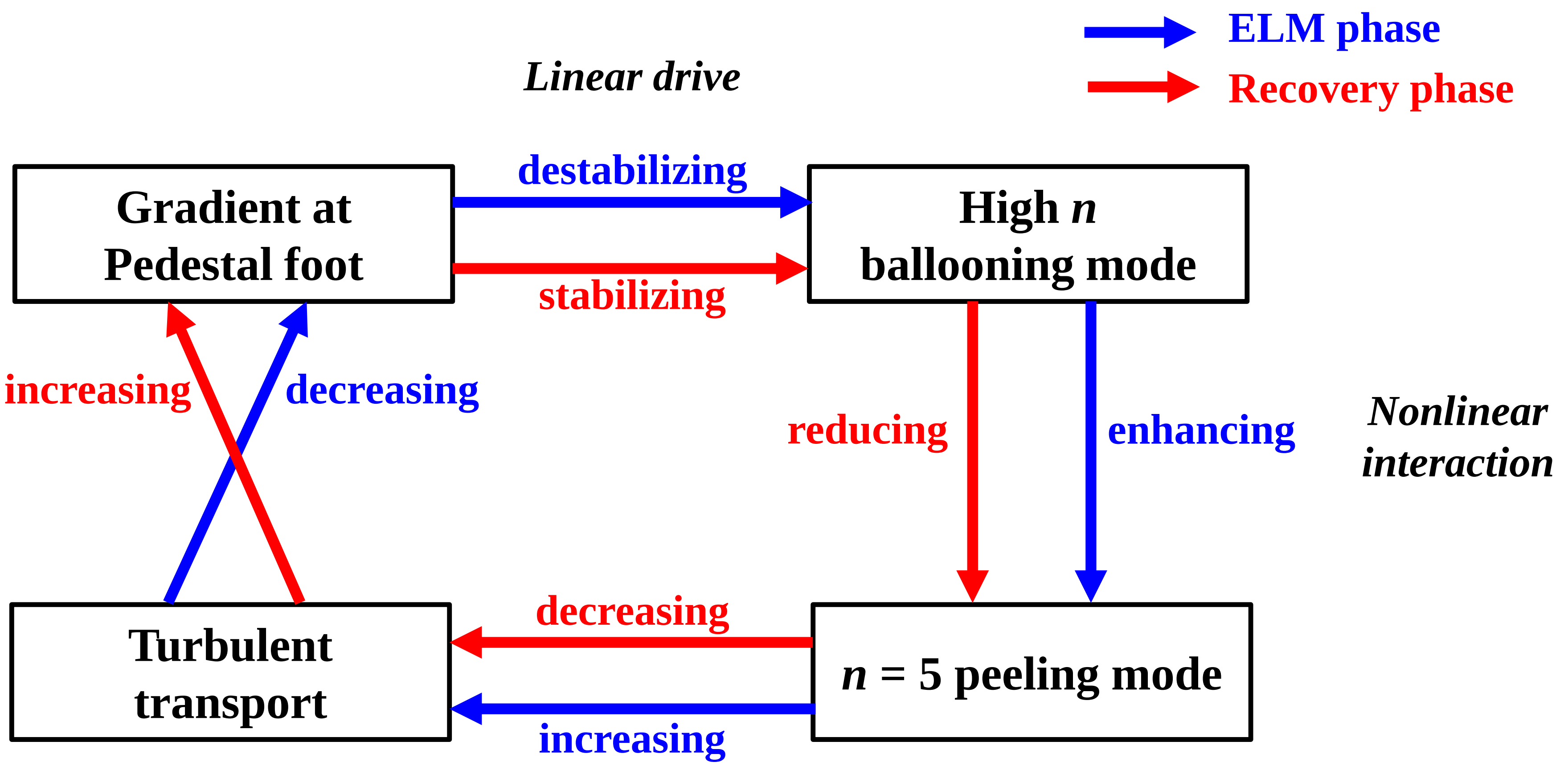






Weak E×B shear at pedestal foot facilitates turbulence transport

Physical mechanism: grassy ELM cycle



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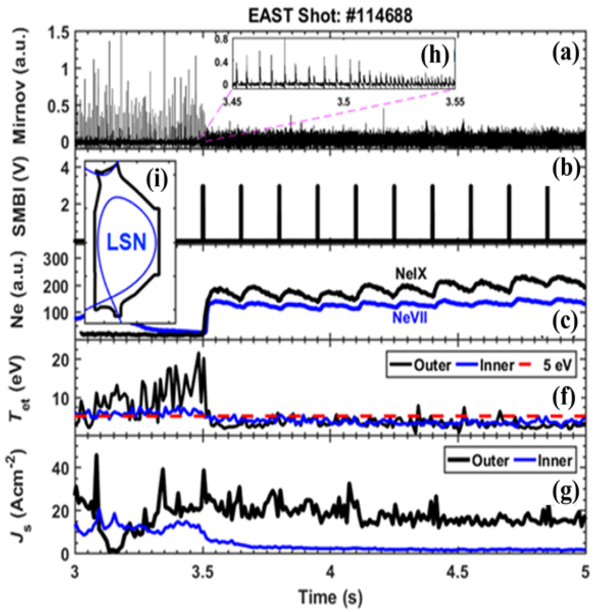
Simulation setup

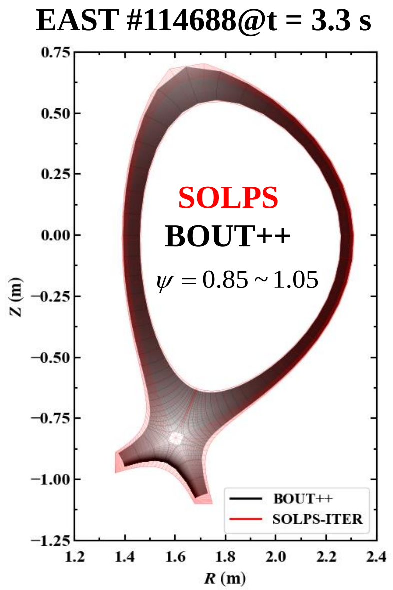
- Simultaneous detachment and ELM mitigation achieved in EAST experiment with Ne injection
- To qualitatively simulate the edge plasma profile evolution after impurity seeding

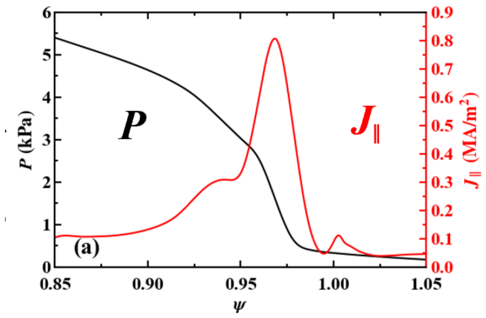
  - **SOLPS-ITER (36×64)**
    - CEI: $n_i = 3.4 \times 10^{19}$ m^{-3}, $P_{SOL} = 3$ MW
    - Include currents and drifts, time-dependent
    - **Impurity seeding with fixed Ne^{8+} density at CEI**
    - **Evolving n_i , T_i , T_e, $J_\parallel$ and ϕ**
  - **BOUT++ (200×64×64)**
    - Six-field two-fluid model, $n = 0$ components fixed
    - **Including impurity effect via vorticity (only Ne^{8+})**
    - **Transport coefficients D_i , V_i and χ_i/χ_e (same for impurities)**

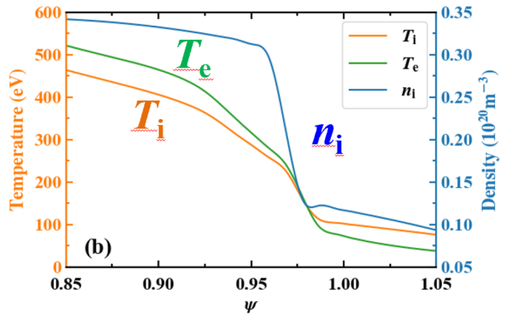
$$\varpi = \frac{n_i m_i}{B_0}\left(\nabla_\perp^2\phi + \frac{1}{Z_i e n_i}\nabla_\perp^2 P_i + \frac{1}{n_i}\nabla_\perp n_i \cdot \nabla_\perp \phi\right)$$

$$\boxed{+\frac{n_{imp} m_{imp}}{B_0}\left(\nabla_\perp^2\phi + \frac{1}{Z_{imp} e n_{imp}}\nabla_\perp^2 P_{imp} + \frac{1}{n_{imp}}\nabla_\perp n_{imp} \cdot \nabla_\perp \phi\right)}$$



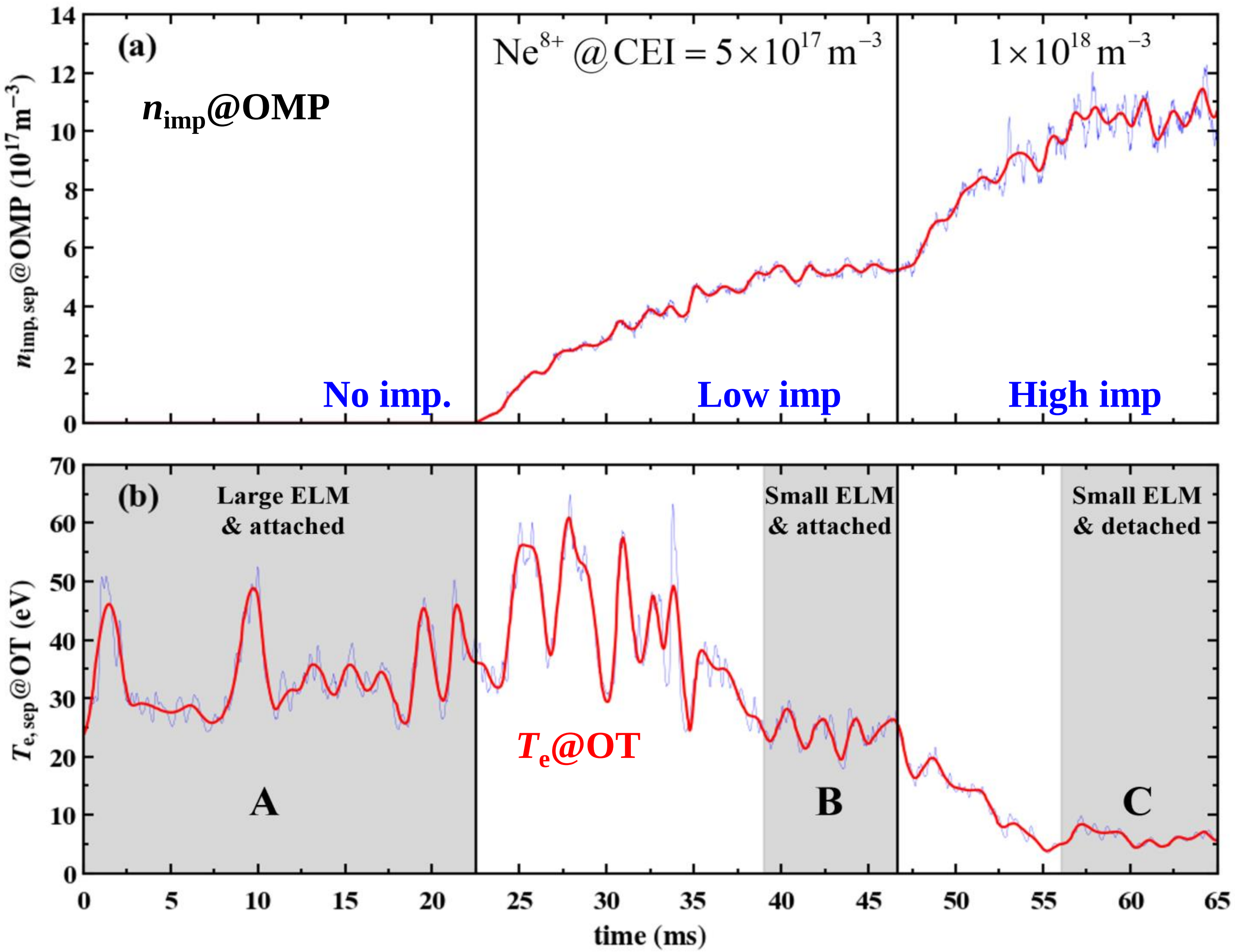






Simulation results

- **Phase A: Large ELMs / attached**
  - No impurity
  - Rapid increase of $T_{e,OT}$ due to large ELM
  - Maximum T_e at SP on OT ≈ 50 eV
- **Phase B: small ELMs / attached**
  - Ne^{8+} density at CEI: 5×10^{17} m^{-3}
  - Dramatic decrease of T_e fluctuation
  - Average T_e at SP on OT ≈ 25 eV
- **Phase C: small ELMs / detached**
  - Ne^{8+} density at CEI: 1×10^{18} m^{-3}
  - T_e fluctuation almost vanishes
  - Average T_e at SP on OT ≈ 5 eV

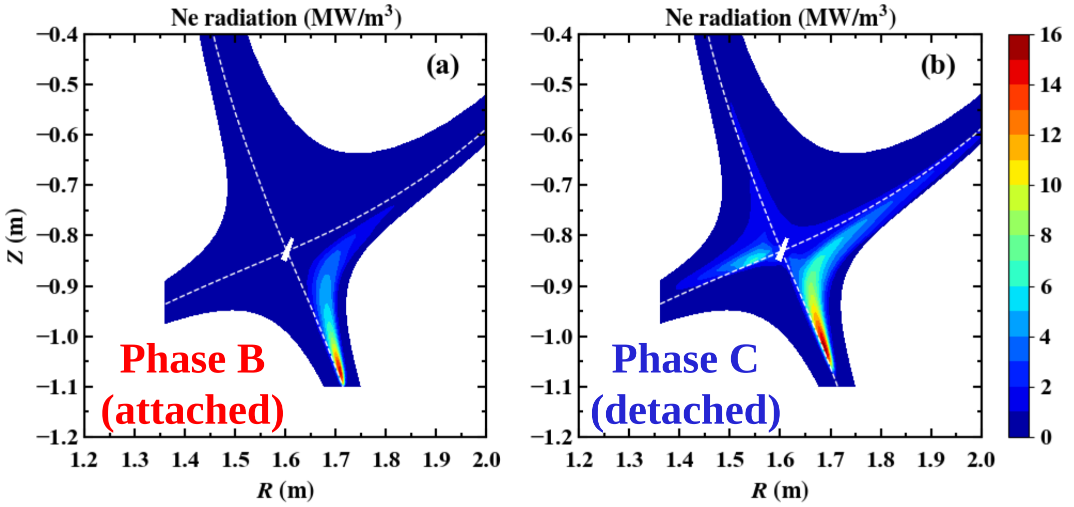


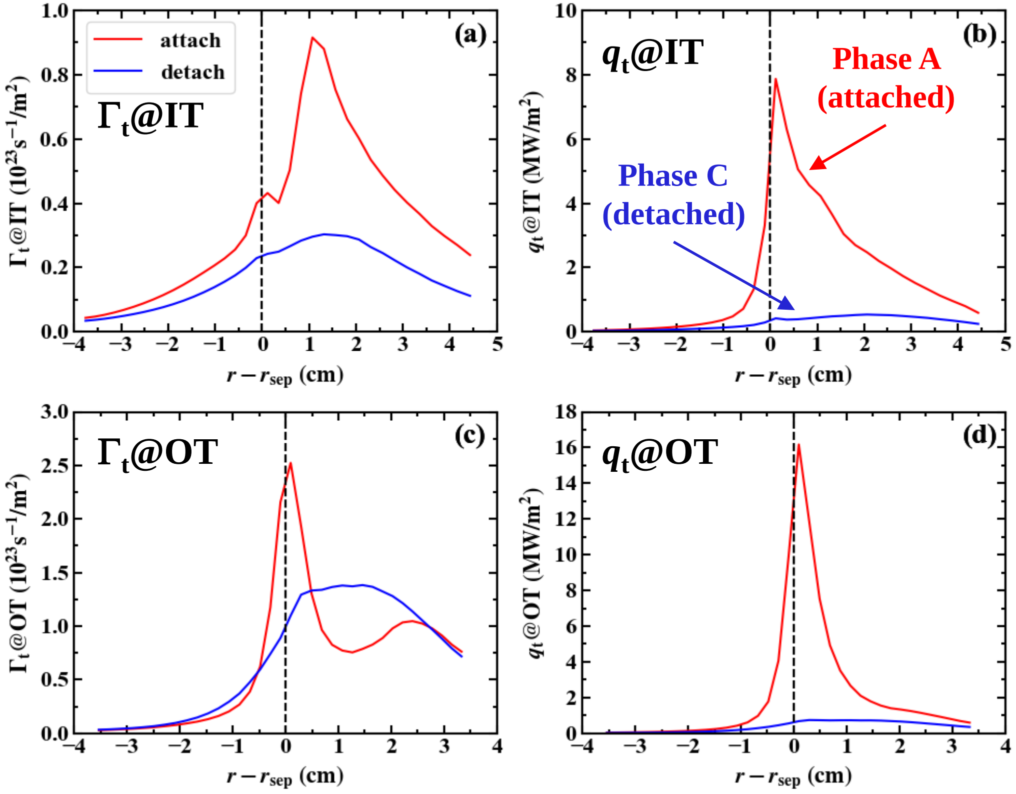
Divertor plasma: attached ⟶ detached

- Both inner and outer divertor achieve **energy detachment**, higher particle detachment level for inner target
  - **Qualitatively consistent with experiment**

A. Leonard, PPCF 2018

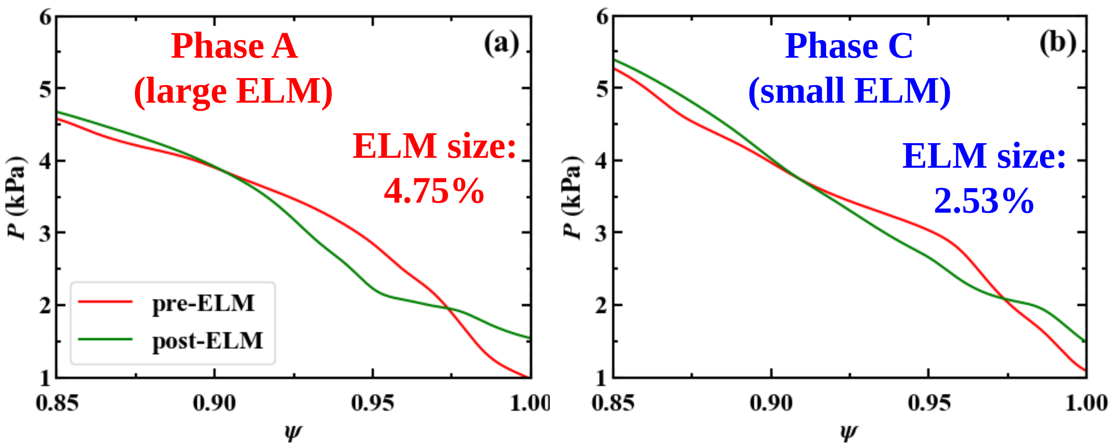
- When approaching detachment, radiation region moves from outer target toward X point
- Total radiation power 2.39 MW (**80% P_{SOL}**), 0.68 MW from core region (**28% radiation fraction**)



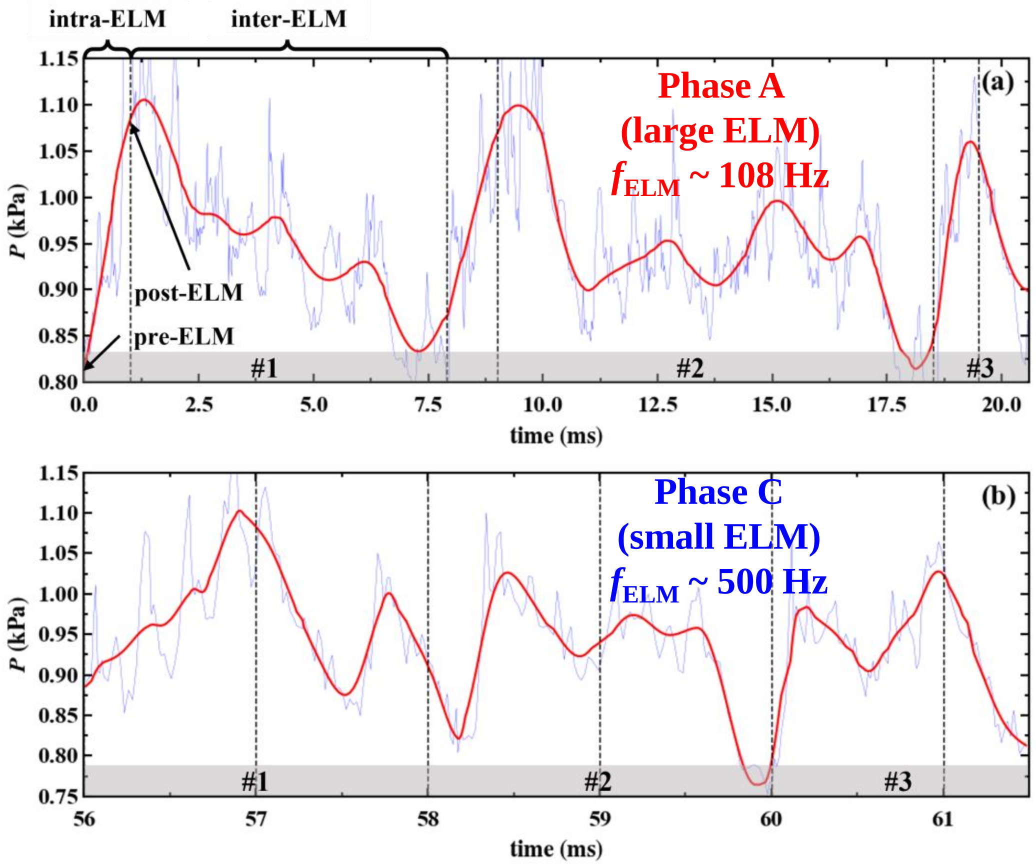


ELM size: large ⟶ small

- Distinct recovery phase following ELM burst for **large ELM (phase A)**: f_{ELM} **~ 108 Hz (Exp. ~ 200 Hz)**
- Quasi-continuous exhaust feature for **small ELM (phase C)**: f_{ELM} **~ 500 Hz (consistent with Exp.)**
- ELM size of **small ELM (2.53%)** is about **half** of that for **large ELM (4.75%)**

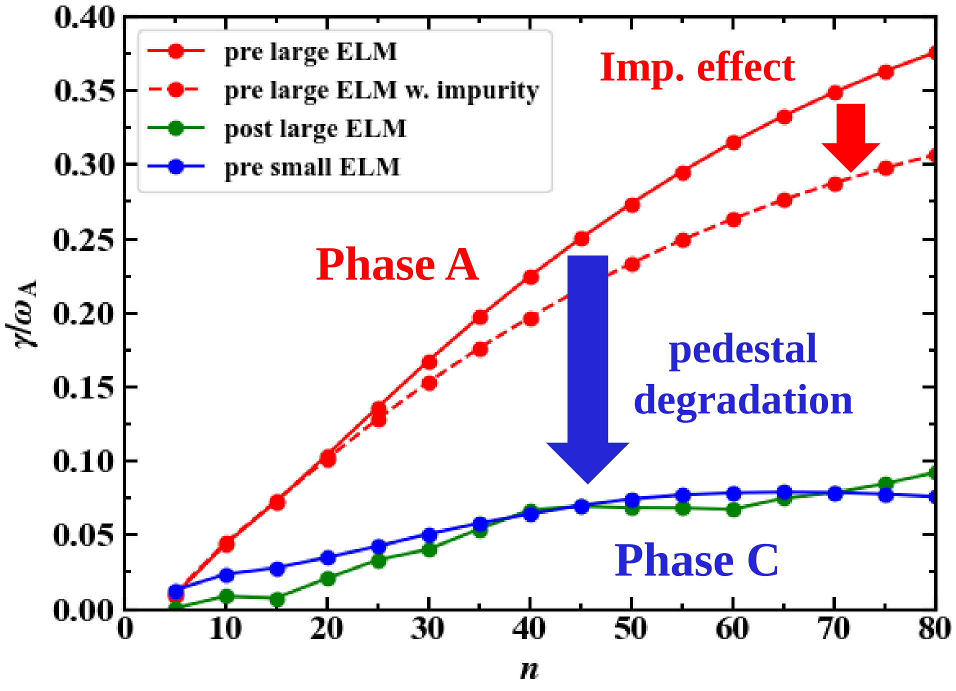


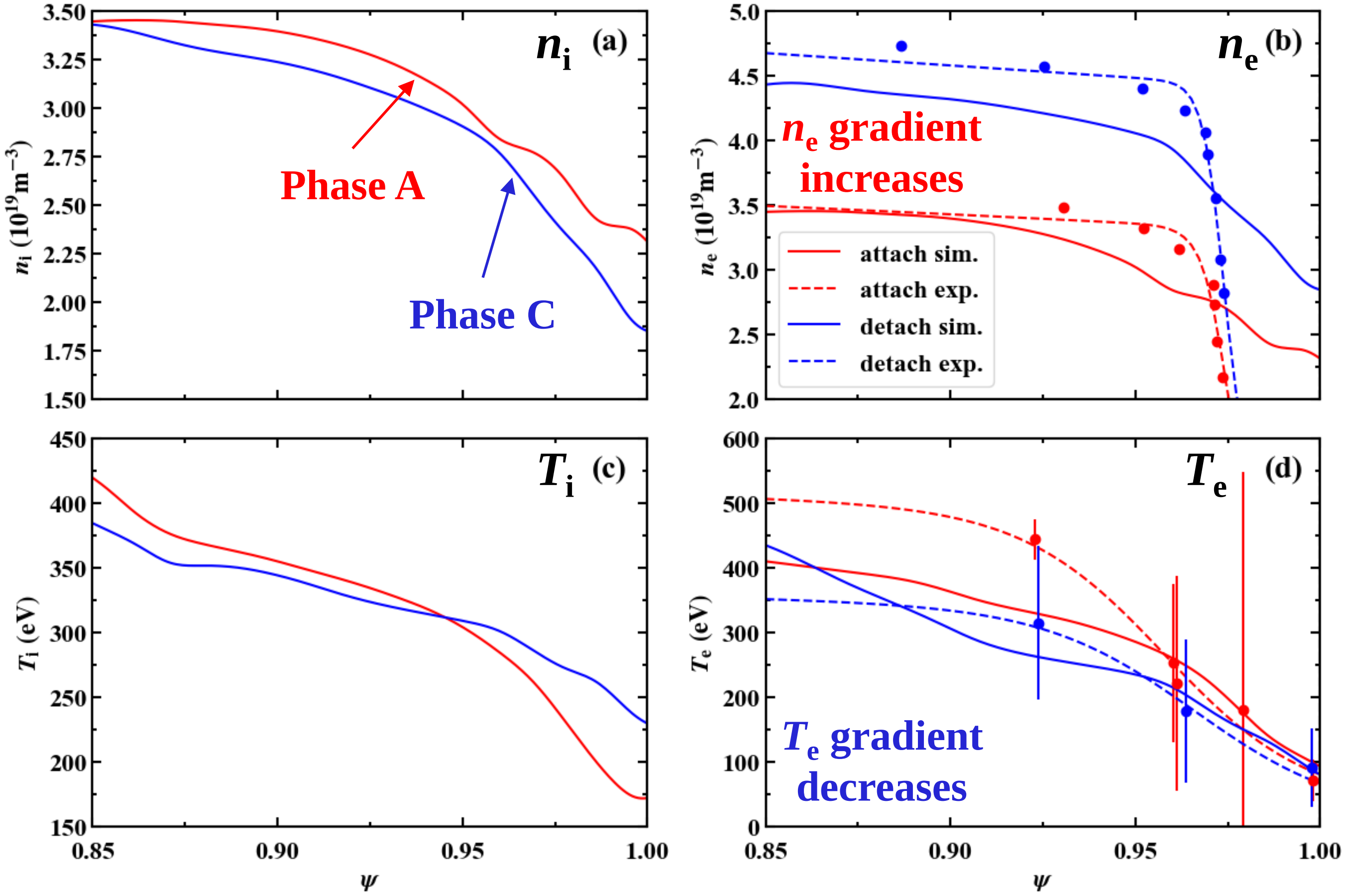
$$\text{ELM size:} = \frac{\Delta W_{ped}}{W_{ped}} = \frac{\int_{\psi_{in}}^{\psi_{out}} d\psi \oiint \sqrt{g}\, d\theta d\zeta \left(P_{\text{pre-ELM}} - P_{\text{post-ELM}}\right)}{\int_{\psi_{in}}^{\psi_{out}} d\psi \oiint \sqrt{g}\, d\theta d\zeta\, P_{\text{pre-ELM}}} \times 100\%$$



ELM mitigation: degradation of pedestal profiles

- **Degradation of pedestal profile** after impurity seeding: **suppress pedestal instabilities**
- **Impurity** itself also has **stabilization effect** → **S.F. Mao, Poster in this meeting #17**





Outline

- Motivation
- Edge plasma coupling simulation framework (EPCS)
- Time-dependent simulation for grassy ELM cycles
- Impurity seeding: simultaneous detachment/ELM mitigation
- Conclusion

Conclusion

- **EPCS framework** is developed for research of physics mechanism behind ELM/detachment control and prediction of edge plasma behavior in future device
- Simulations are performed based on EAST experiments
  - **Grassy ELM:**
    - ELM frequency ~ 2 kHz and counter-clockwise trajectory in P-B diagram: consistent with experiment
    - At pedestal foot: high *n* ballooning mode → nonlinearly enhancing peeling mode → ELM burst
    - Strong turbulent particle transport at pedestal foot: facilitates maintaining of low density gradient
  - **Simultaneous detachment and ELM mitigation by neon impurity injection:**
    - After impurity seeding, large ELM→small ELM and attachment →energy detachment
    - ELM mitigation mainly due to the degradation of pedestal profile after impurity seeding
- Next step:
  - Validation (and investigation) for more experiments and devices. Welcome collaboration!
  - Development with more physics model (e.g. micro-turbulence)
  - Simulation for reactor level devices (prediction)

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Thanks for your attention!