BOUT++ simulations of small ELM dynamics and associated SOL width broadening

BOUT++
Boundary Plasma Turbulence Code

Nami Li[1*]

X. Q. Xu[1], P.H. Diamond[2], Y. F. Wang[3], X. Lin[3], N. Yan[3] Z.Y. Li[3] and G. S. Xu[3]

[1]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

[2]University of California at San Diego, CA 92186, USA

[3]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

[*]li55@llnl.gov

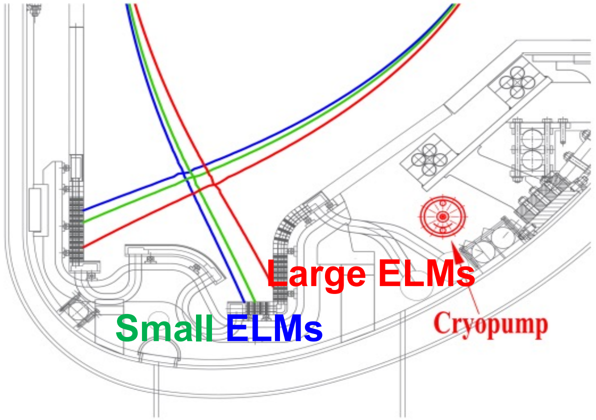
BOUT++ 2023 workshop
January 9-11, 2023
Lawrence Livermore National Laboratory, Livermore, CA

Fusion Energy Sciences

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under DE-AC52-07NA27344. LLNL-PRES-843807

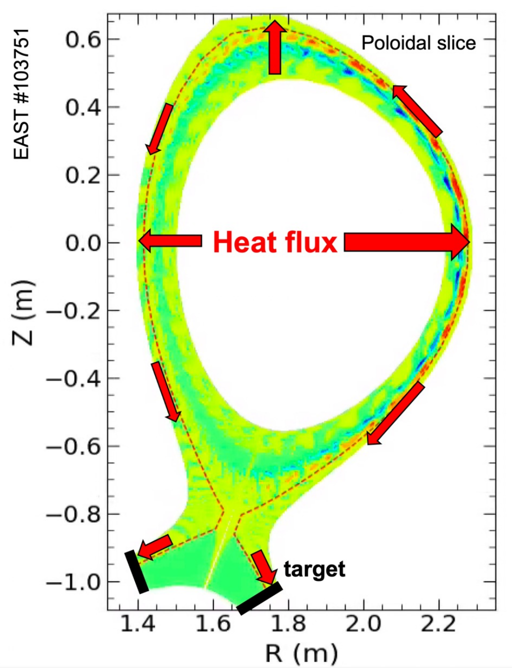
BOUT++ simulations are performed to investigate the underlying physics of small ELMs dynamics and the associated SOL width broadening

- Small ELMs have been achieved by controlling strike points from vertical to horizontal divertor plates in EAST expts.



- 6-field 2-fluid turbulence code (6F):
  - ✓ Ion density n_i, ion and electron temperature T_i, T_e, ion parallel velocity $V_{\parallel i}$, parallel magnetic vector potential $A_\parallel$ and vorticity ϖ equations
  - ✓ Peeling-Ballooning modes, Drift-Alfvén modes, ion diamagnetic effect, resistivity, parallel thermal conductions, etc.

- Small ELMs physics: turbulence spreading and its impact on heat flux width broadening
  - ✓ Based on EAST expts, 20 simulations for a scan
    - Pedestal collisionality ν^*
    - Pedestal density width/gradient ∇n
    - Pedestal radial electric field (Er)



Small ELMs can be triggered by increasing separatrix density and/or decreasing pedestal density gradient

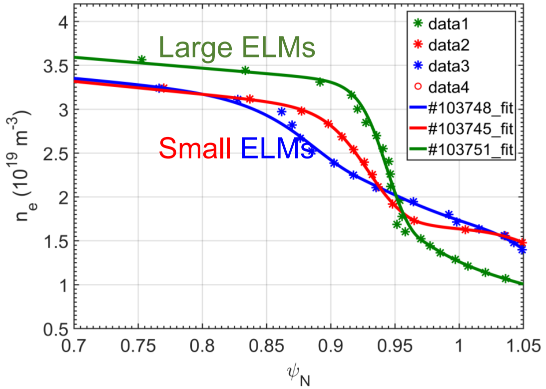
1. **Small ELMs have been achieved with increasing SOL density by controlling strike points from vertical to horizontal divertor plates as demonstrated in EAST expts.**

✓ Small ELMs can be triggered, either with

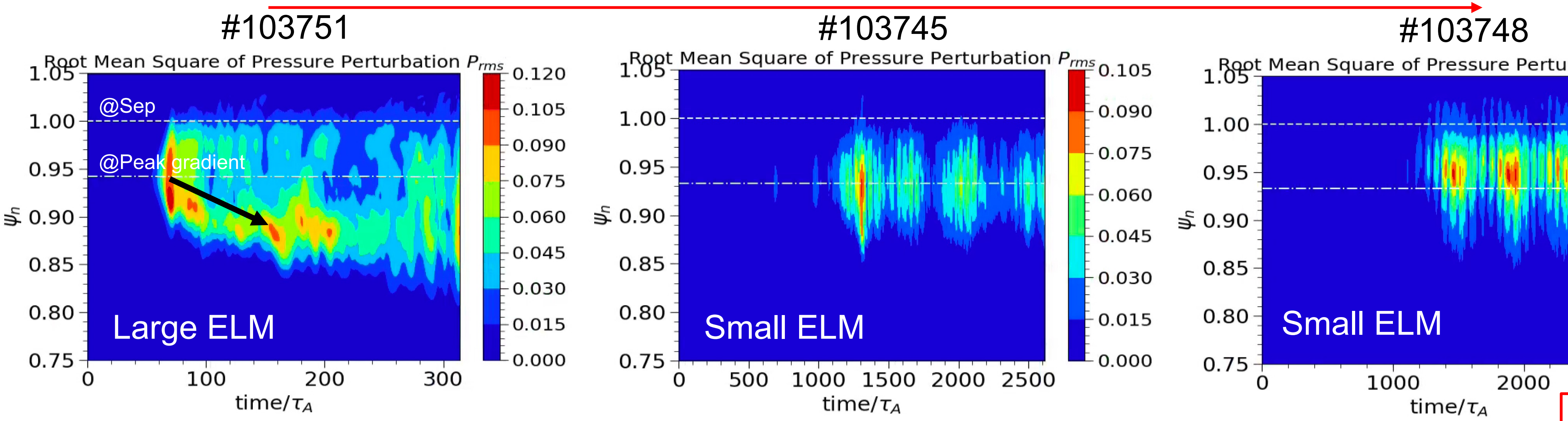
- the ideal peeling-ballooning mode near the peak gradient of the pressure (#103745)

  or

- Local ballooning instability near separatrix (#103748)



Separatrix density increasing (pedestal density gradient decreasing)



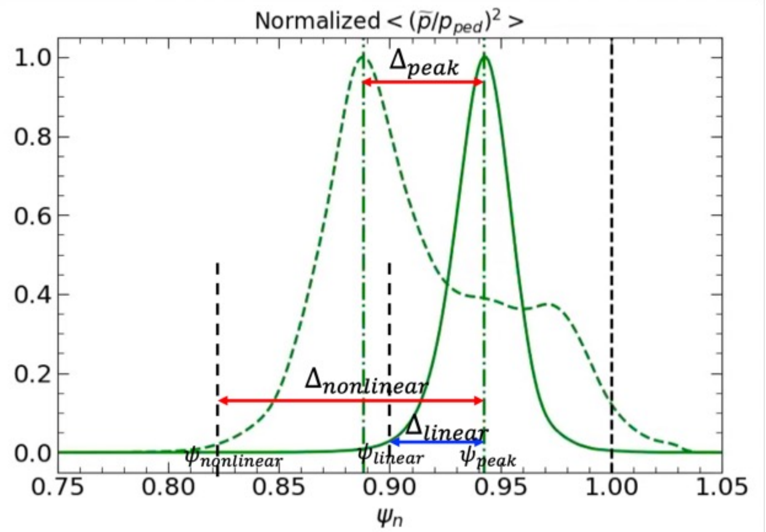
Nami Li, PoP2022

Small ELMs can be triggered by marginally unstable modes

- **Linear: in close proximity to instability threshold for**
  - ✓ low-n peeling mode
  - ✓ high-n ballooning mode
  - ✓ intermediate-n peeling-ballooning mode
  - ✓ Local ballooning instability near separatrix

- **Nonlinear:**
  - ✓ Inward avalanche due to multiple pedestal crashes→ large ELMs
  - ✓ Inward turbulence spreading from linear unstable zone to stable zone → small ELMs

- **Inward fluctuation intensity spreading**
  - The front propagation follows the sequence of multiple profiles collapsing: Δ_{peak}
  - The inward penetration as the intensity radial profile broadening: $\Delta_{nonlinear} - \Delta_{linear}$



Small or large ELMs strongly depend on the inward fluctuation spreading from linear unstable zone to stable zone

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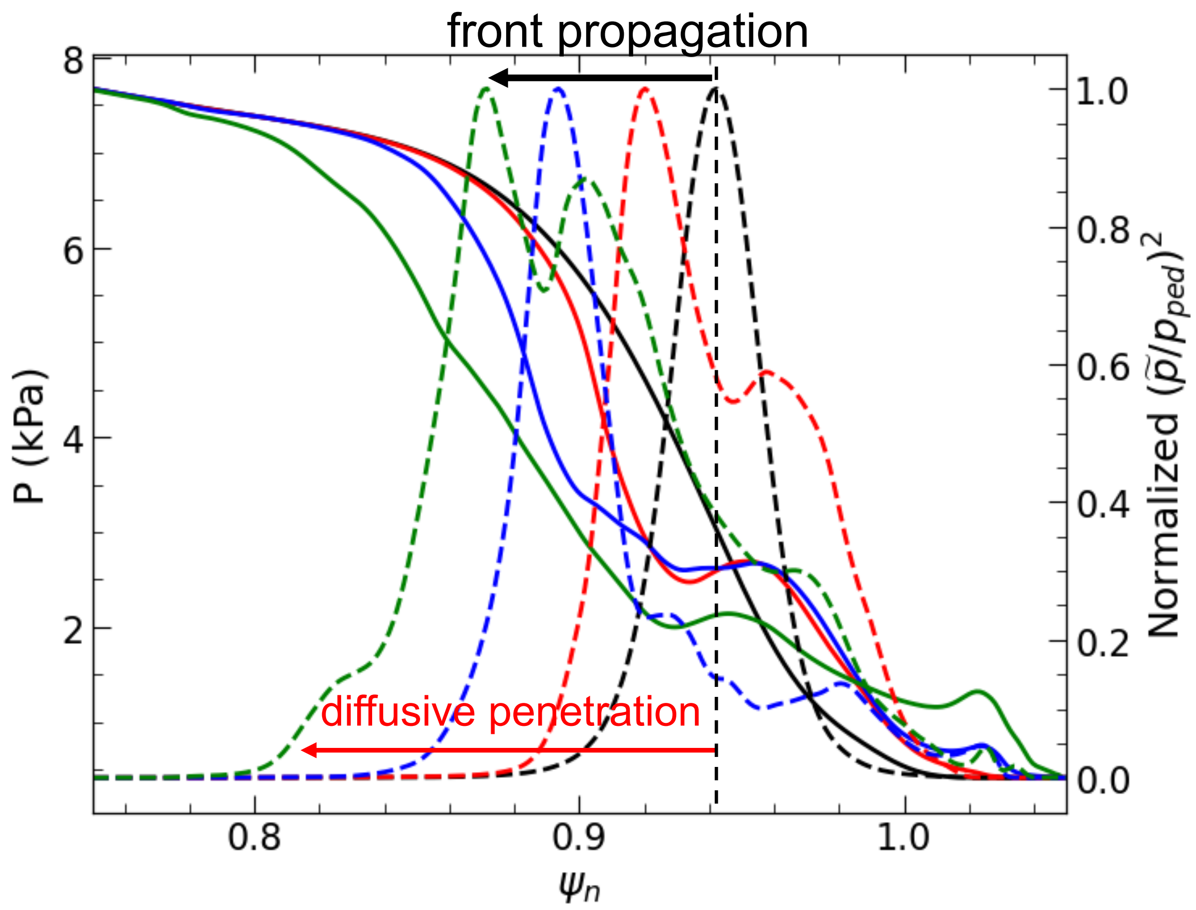

❖ **For the large ELM (type-I ELM)**

- ✓ **The linear mode (peeling-ballooning) is very unstable with large linear growth rate in the pedestal**
- ✓ **The pressure fluctuation intensity at the onset of nonlinear phase is much stronger than that of the small ELM**
- ✓ **Inward avalanche**:

The high pressure fluctuation intensity → pedestal collapses → profile steepening inward → pedestal top gets into linear unstable zone → fast front propagation and deep diffusive penetration

Small or large ELMs strongly depend on the inward fluctuation spreading from linear unstable zone to stable zone

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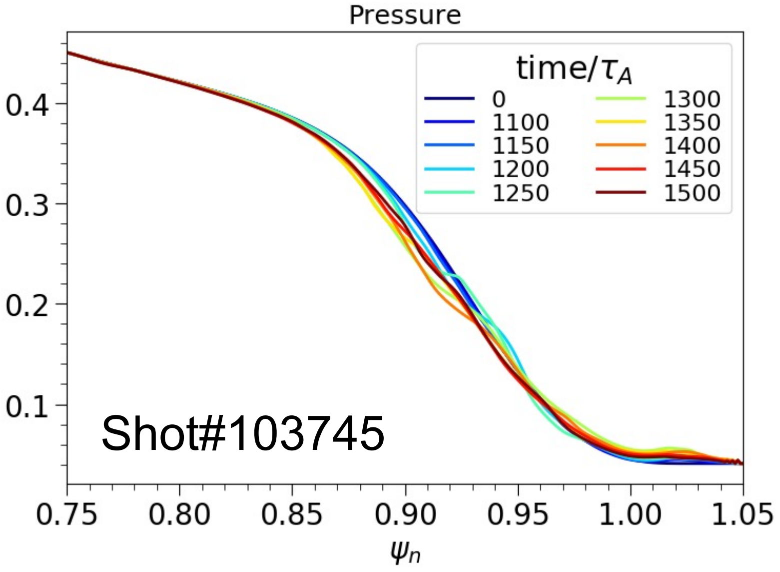
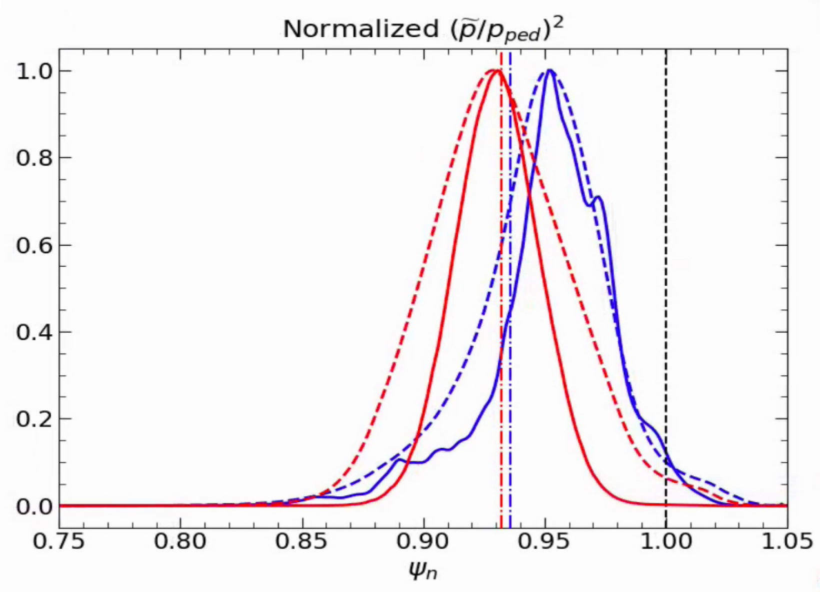
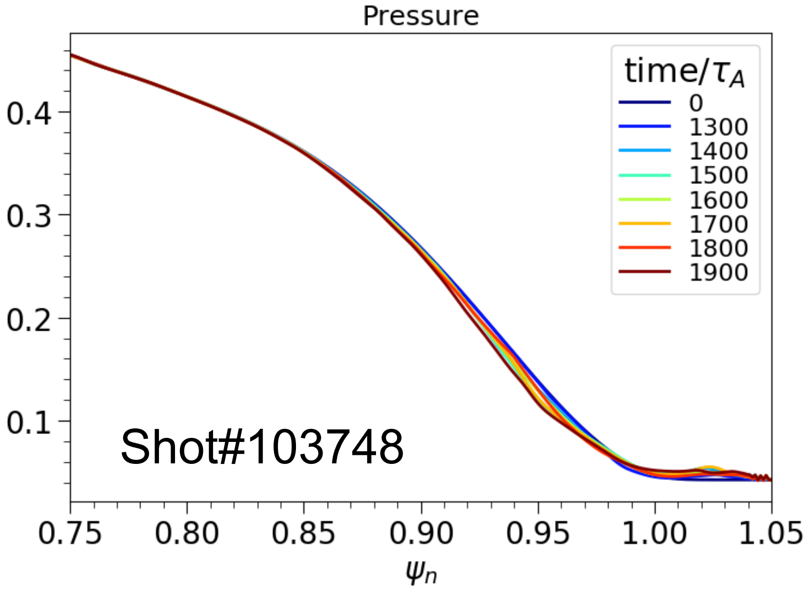
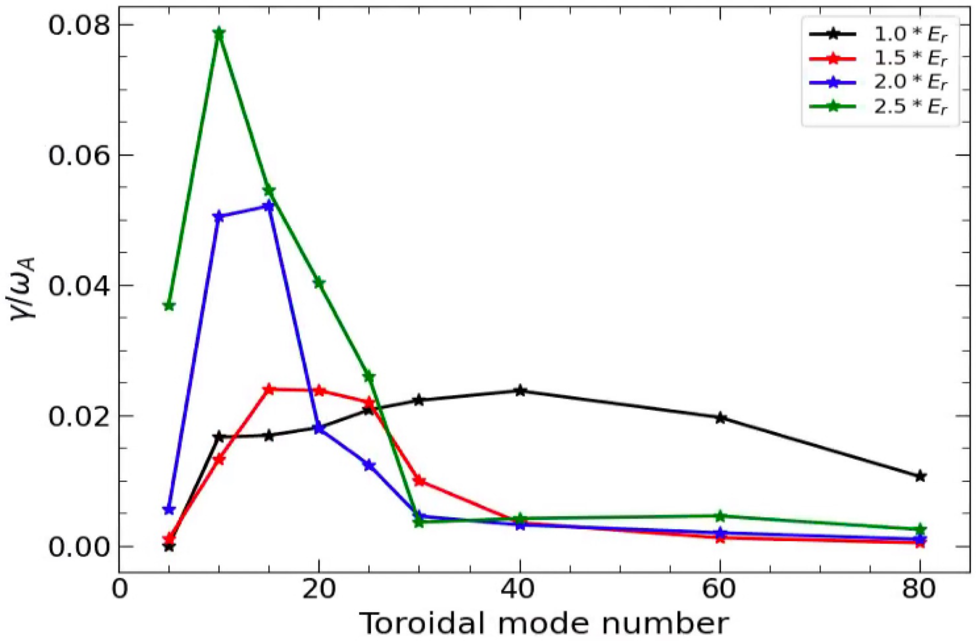


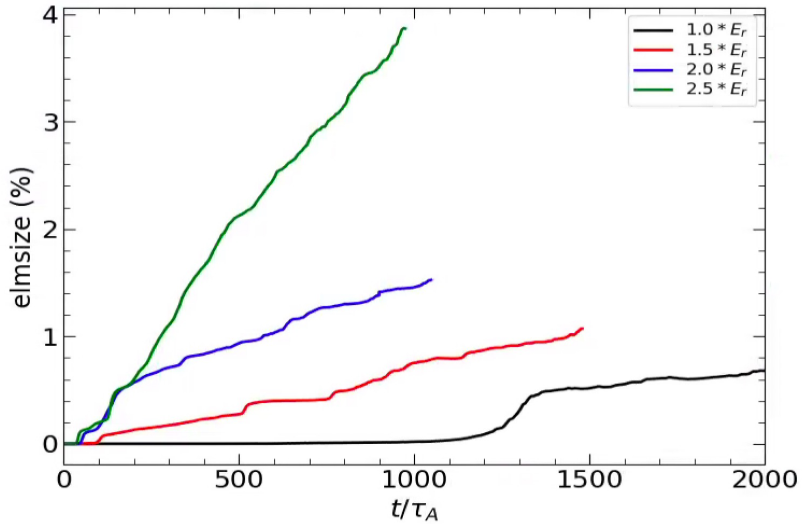


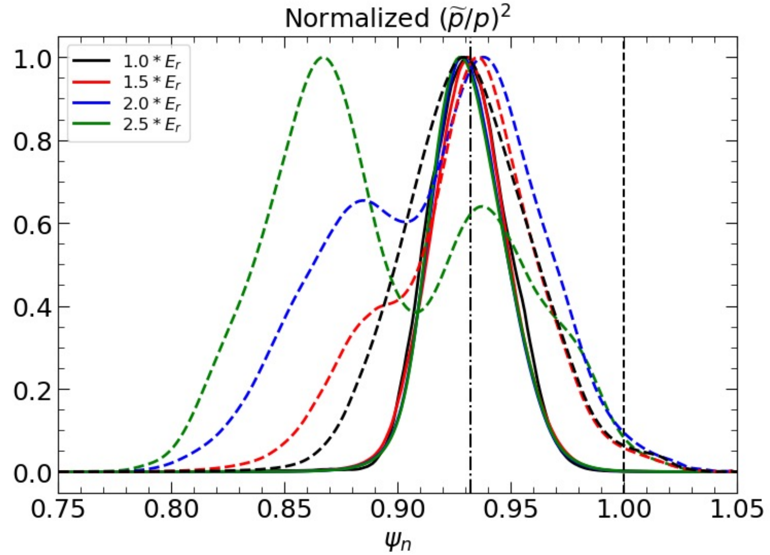


- **For the small ELMs**
  - ✓ **small ELMs can be triggered by marginally unstable mode**
    - **low-n peeling mode, high-n ballooning mode or intermediate-n peeling-ballooning mode**
    - **The fluctuation intensity is low → pedestal gets into linear stable zone after the initial ELM crash→ there is no clear front propagation but with both inward and outward turbulence spreading**

A transition occurs from small ELMs to large ELMs with increasing pedestal ExB shear flow





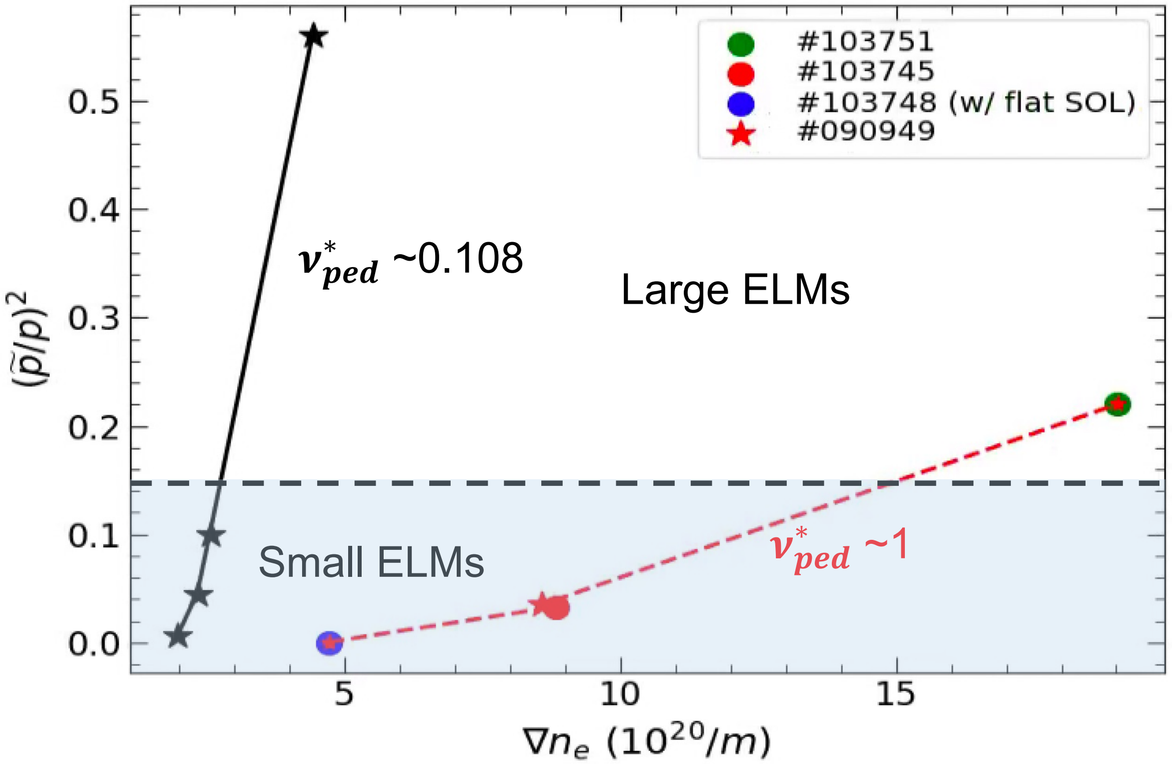


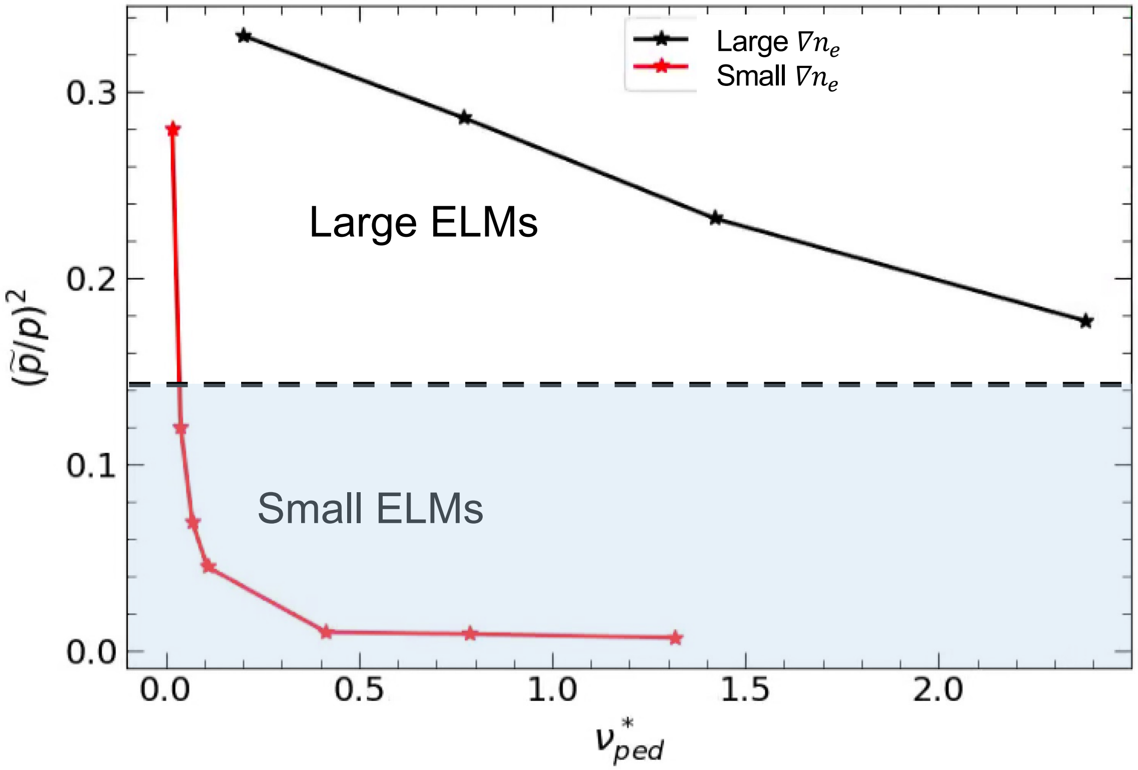
- **With increasing pedestal Er**
  - ✓ **The dominant mode shifts from high-n to low-n with a narrow mode spectrum**
  - ✓ **The maximum linear growth rate increases**
  - ✓ **The ELM size increases**
- **The ELM size depends strongly on the inward penetration depth** $\Delta\psi_n$

Small ELMs (reducing the ELM size):

How do pedestal plasma parameters impact on the turbulence spreading from pedestal to SOL?

Turbulence spreading increases as pedestal density gradient increases and pedestal collisionality decreases





- **Fluctuation intensity $(\tilde{p}/p)^2$ at LCFS increases as pedestal gradient (∇n_e or ∇P_0) increases**
  - **Small ELMs**
    - ✓ **With high v^*_{ped}: wide range of ∇n_e or ∇P_0 window**
    - ✓ **With low v^*_{ped}: narrow range of ∇n_e or ∇P_0 window**

- **Fluctuation intensity $(\tilde{p}/p)^2$ at LCFS increases as pedestal collisionaltiy v^*_{ped} decreases**
  - **Small ELMs**
    - ✓ **With large ∇n_e or ∇P_0 : very high v^*_{ped}**
    - ✓ **With small ∇n_e or ∇P_0 : wide range of v^*_{ped} window**

Small ELMs:

How does turbulence spreading affect the SOL width broadening?

We introduce fluctuation energy intensity flux $\boldsymbol{\Gamma_{\varepsilon}}$ at LCFS to measure turbulence spreading from pedestal into the SOL

$$\boldsymbol{\Gamma_{\varepsilon} = c_s^2 \left\langle \widetilde{V_r} (\widetilde{p}/p)^2 \right\rangle}$$

Divertor heat flux width is broadened in the small or grassy ELM regime due to the large turbulence transport

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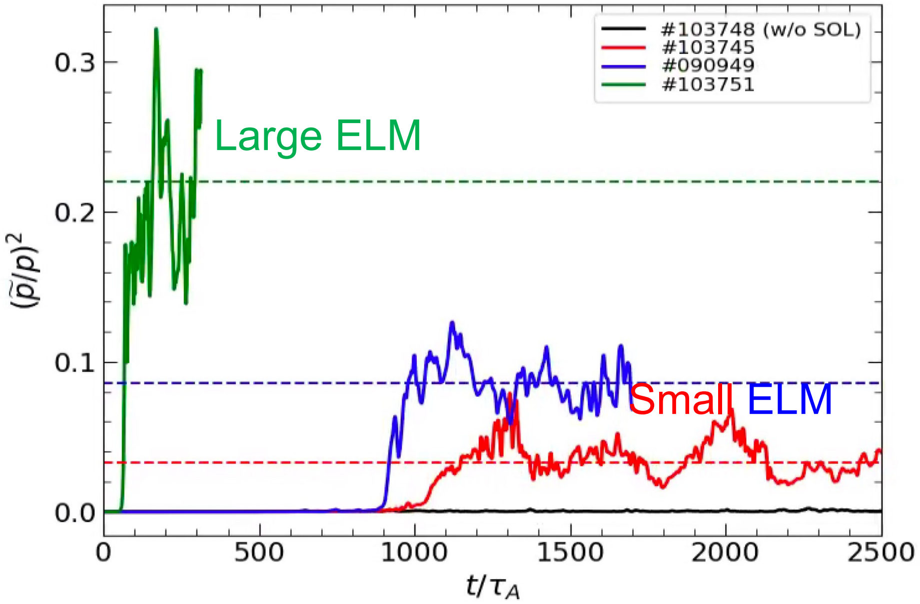
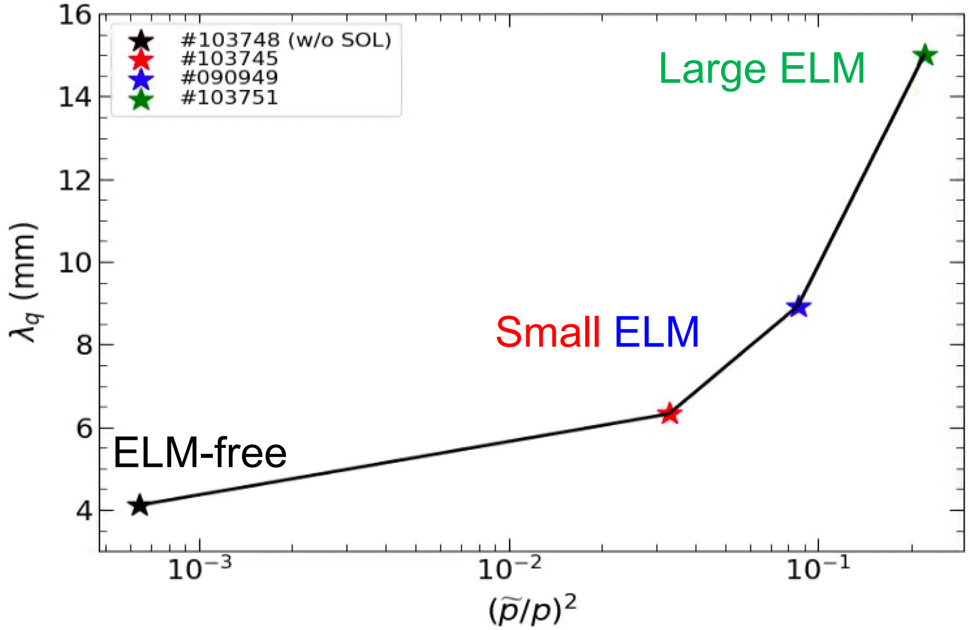


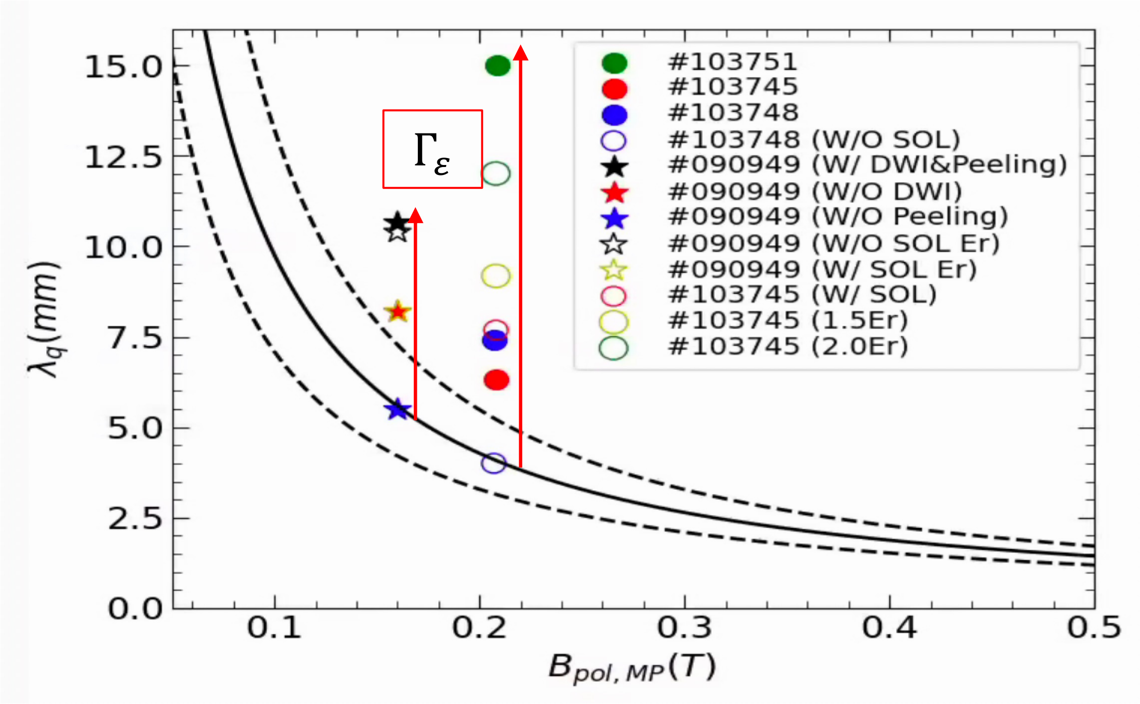


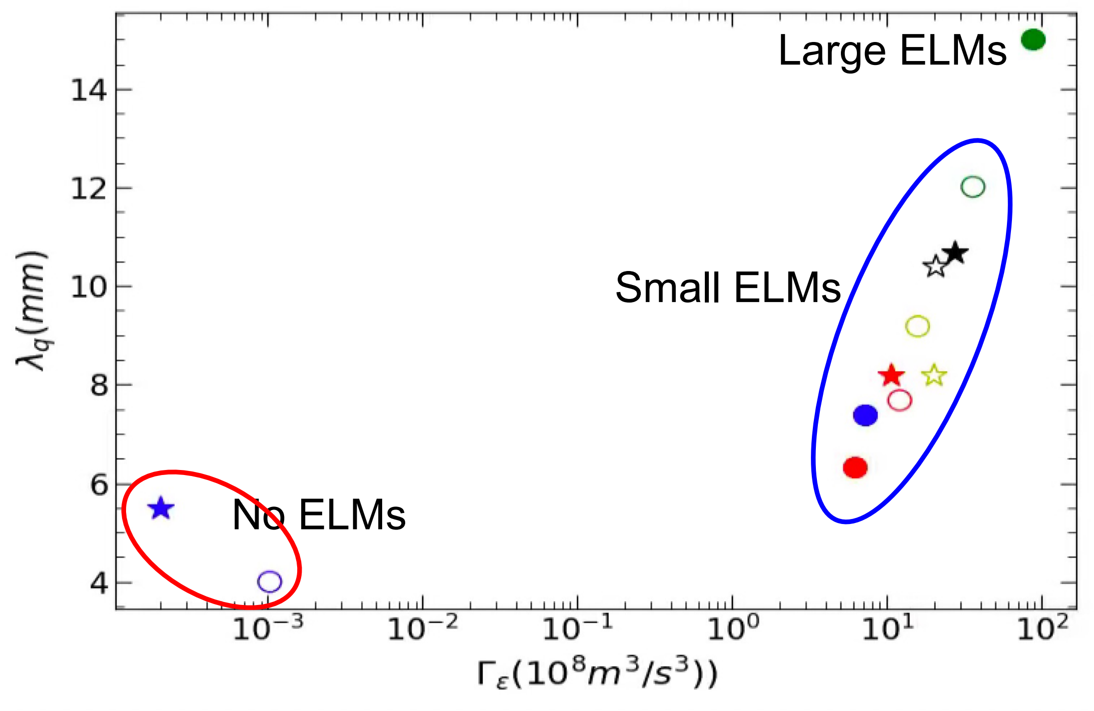
- ❖ λ_q **increases with fluctuation intensity** $(\tilde{p}/p)^2$ **increasing at LCFS**
- ❖ **From small ELM to large ELM,** λ_q **is significantly broadened**

BOUT++ turbulence simulations show λq is significantly broadened from ELM-free to small ELM regime as fluctuation energy intensity flux increases

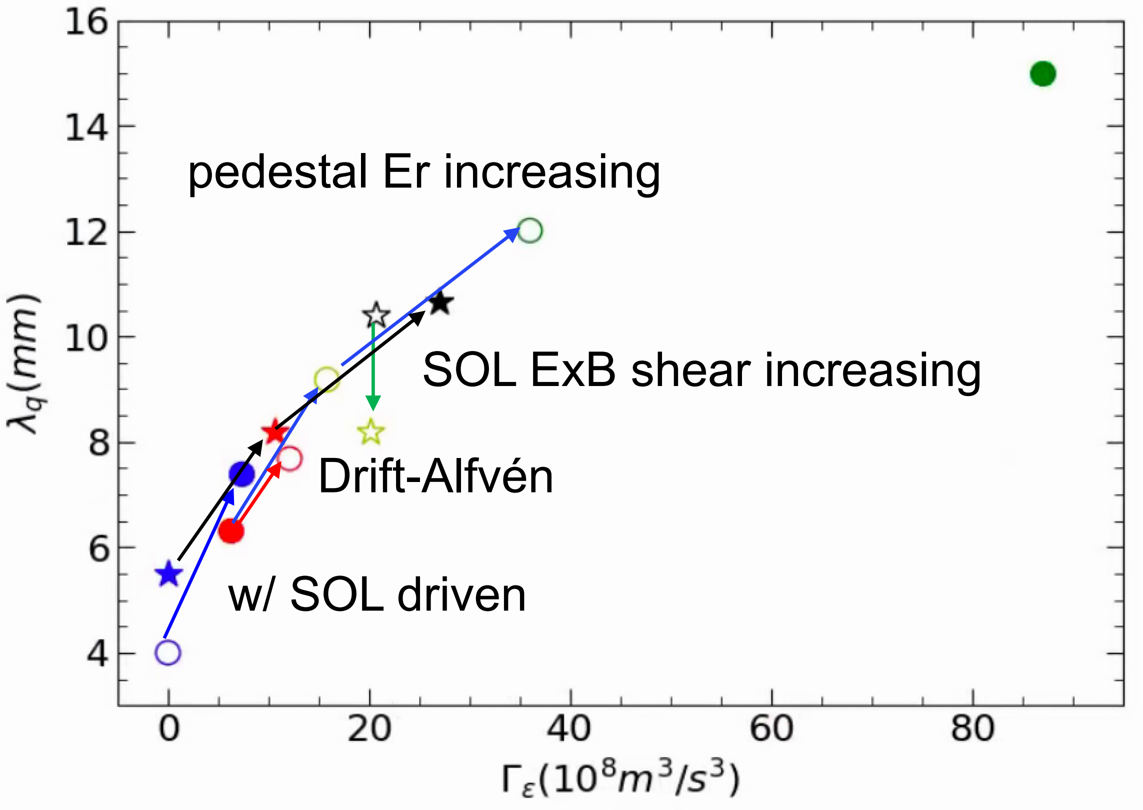
- **Divertor heat flux width is broadened by a larger radial turbulence transport**
  - ✓ **Fluctuation energy intensity flux Γ_ε at LCFS measures the turbulence spreading from pedestal into the SOL**
  - ✓ **Heat flux width increases with Γ_ε increasing**

$$\Gamma_\varepsilon = c_s^2 \langle \tilde{V}_r (\tilde{p}/p)^2 \rangle$$





BOUT++ turbulence simulations show the SOL width λq is significantly broadened via controlling of edge fluctuation



$$\Gamma_\varepsilon = c_s^2\langle \tilde{V}_r(\tilde{p}/p)^2\rangle$$

- **λq is broadened by increasing fluctuation energy intensity flux Γ_ε at LCFS[1]**
- **Drift-Alfvén turbulence enhances the turbulence spreading from pedestal to SOL, leading to SOL width broadening**
- **λq increases with increasing SOL local instabilities**
- **λq increases with increasing Er shear flow in the pedestal**
  - ✓ The stronger Er shear flow shifts the most unstable modes to lower-n and narrows the mode spectrum [2,3] → fluctuation energy intensity flux Γ_ε↑→ pedestal turbulence spreading enhanced

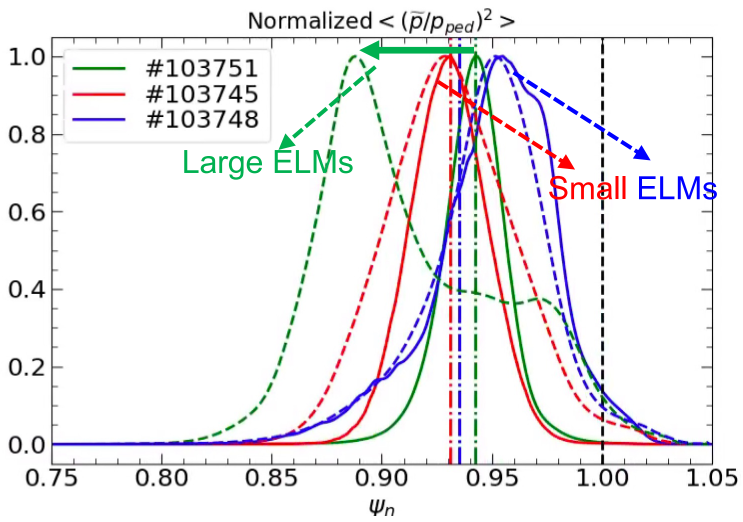
$$E_r = \frac{\nabla P_i}{Z_i e n_i} - V_{\theta i} B_\phi + V_{\phi i} B_\theta.$$

- **λq decreases with sufficiently increased SOL ExB shear –** shear suppression of turbulence spreading

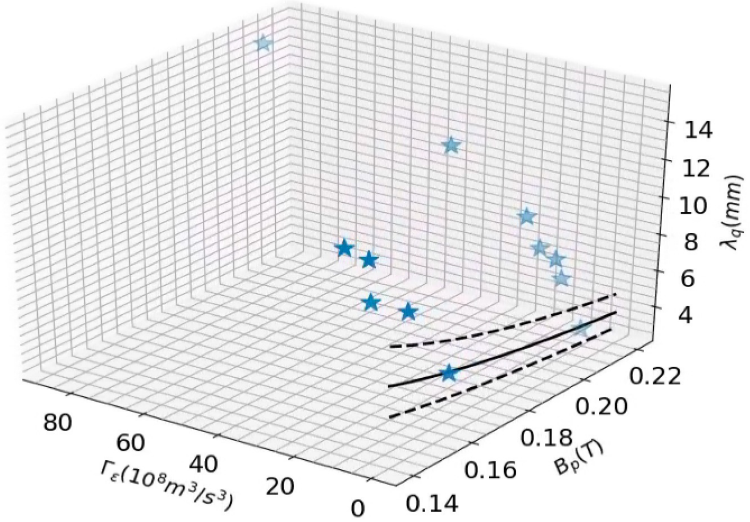
[1] Xu Chu et al., NF 62 (2022) 066021, [2] *Y. Zhang et al., PoP* 26, 052508 (2019); [3] J.G. Chen et al., *PoP* 24, 050704 (2017)

Summary

- Operating in H-mode with small ELMs offers promise to solve two critical problems: reducing the ELM size and broadening the SOL width
- Small or large ELMs strongly depends on the inward fluctuation propagation from linear unstable to stable zone as profile evolves
  - ✓ High fluctuation intensity → multiple profile crashes → fast front propagation and deep penetration → large ELM (inward avalanche)
  - ✓ In close proximity to the instability threshold → low fluctuation intensity → no clear front propagation → small ELM (turbulence spreading)



- SOL width is significantly broadened from ELM-free to small ELM regime due to the strong radial turbulence transport
  - ❑ The width λq can be broadened as
    - ✓ fluctuation energy intensity flux Γ_ε at LCFS increases
      - Enhanced the Drift-Alfvén turbulence
      - Increasing SOL local turbulence
      - Increasing pedestal Er flow shear, decreasing SOL ExB shear



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Thanks for your attention!

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