BOUT++ electromagnetic turbulence simulations of edge plasma dynamics during thermal quench

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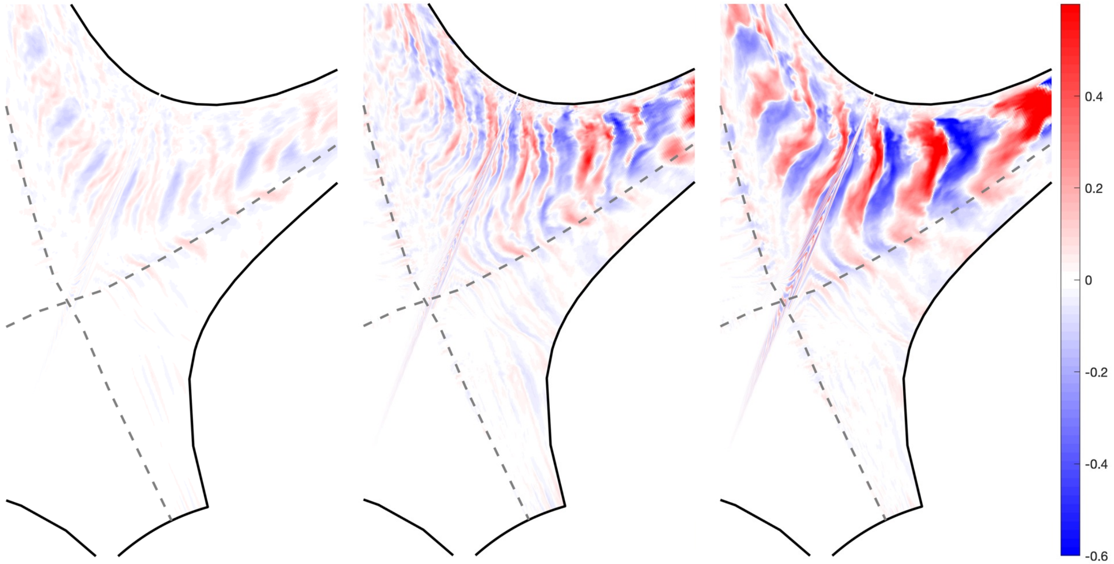
Key Results

- Reproduces several experimental observations qualitatively
- Both ExB turbulent convection and parallel advection processes contribute to radial transport
    - Edge turbulence dominates the cross-field transport and largely determines divertor heat load
    - **Amplified magnetic fluctuation (~10^{-4}) results in stochastic magnetic field-lines that plays an important role of electron radial heat transport and contributes to heat flux width broadening (at the later stage)**
    - The (average) connection length of stochastic field-lines likely impacts the thermal quench energy deposition time

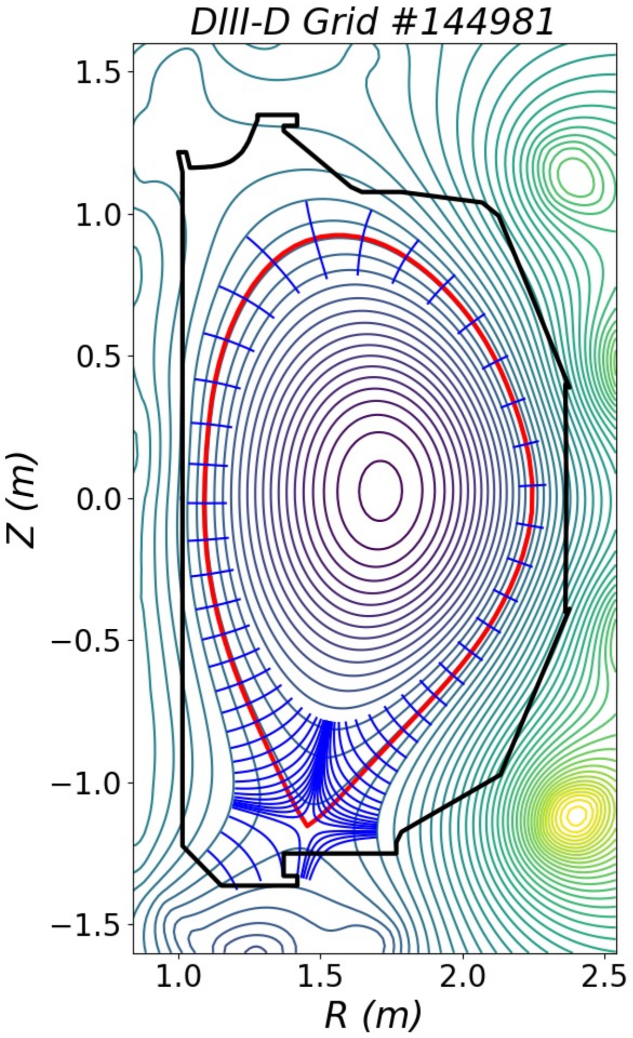
Outline

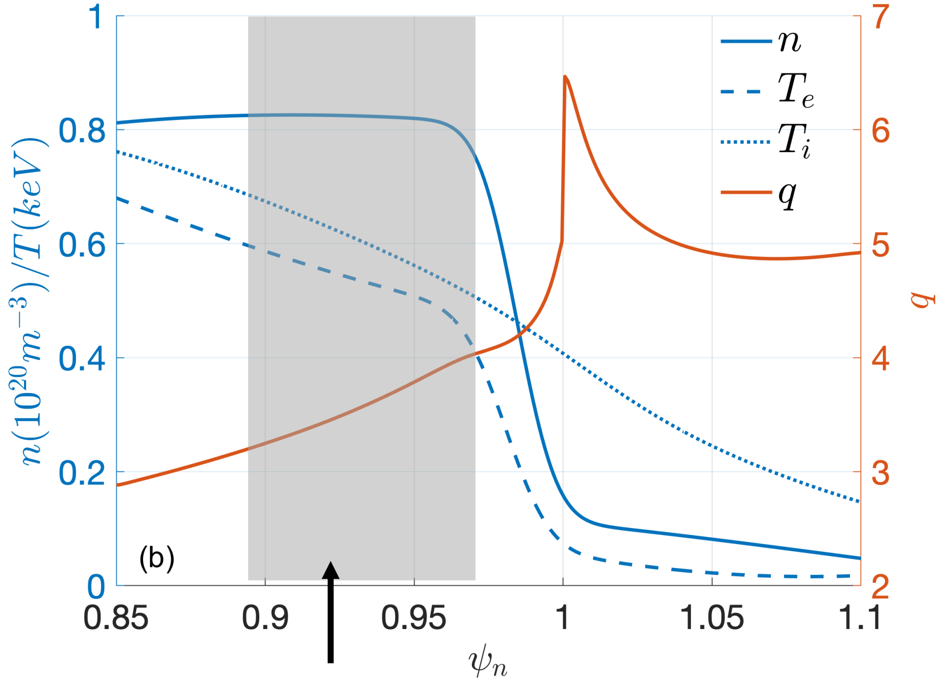
- Introduction
- Numerical model and setup
- Nonlinear simulation results
  - Observation of divertor heat load surging and flux width broadening
  - Role of enhanced edge turbulence
  - Role of enhanced magnetic perturbation
- Summary



Excessive flux driven simulations of DIII-D configuration

- BOUT++ six-field electromagnetic turbulence model[1] is used to simulate DIII-D LSN H-mode plasma with transient but intense flux-driven energy (particle) source at pedestal top



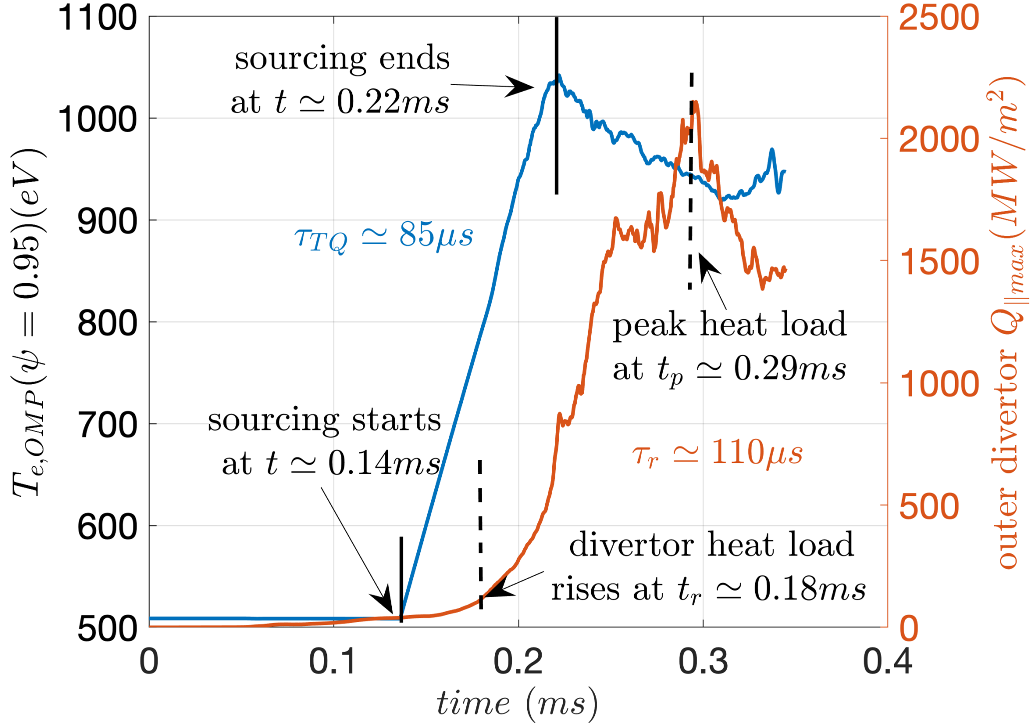


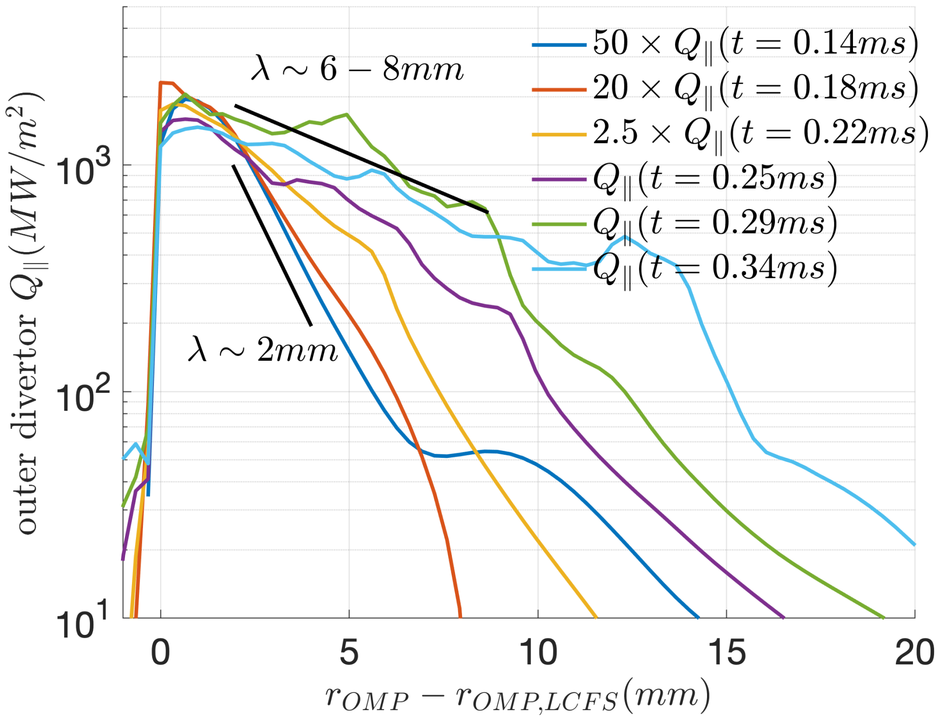
energy (particle) injection region

- $P_{inj} = 1GW$
- equally partitioned between electrons and ions
- radially Gaussian between psi=0.89-0.97
- toroidally and poloidally uniform
- last for 85us
- $E_{inj} = 85kJ$, roughly 15% of total stored plasma thermal energy

[1] Zhu, Seto, Xu and Yagi, Comput. Phys. Commun. (2021)

Outer divertor heat load evolution in BOUT++ simulation





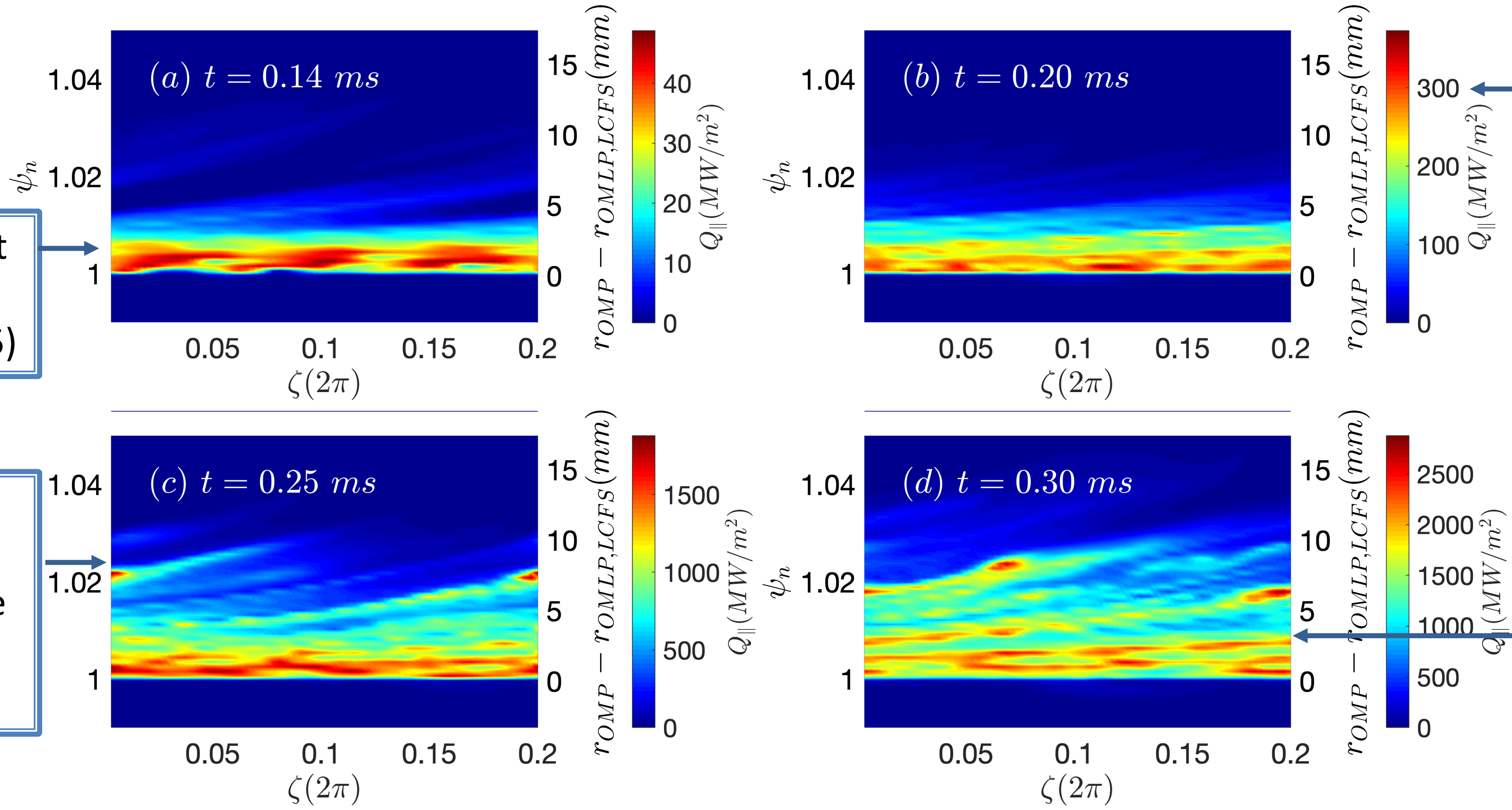
Peak heat flux increases significantly as the pedestal top temperature rises.

$$\tau_r \simeq 110\mu s \sim \tau_{TQ} \simeq 85\mu s$$

From outer divertor parallel heat flux profiles:

- 50x larger amplitude 40MW/m^2 to 2GW/m^2
- 3-4x wider width – from 2mm to 6-8mm

Non-axisymmetric outer divertor heat flux footprint



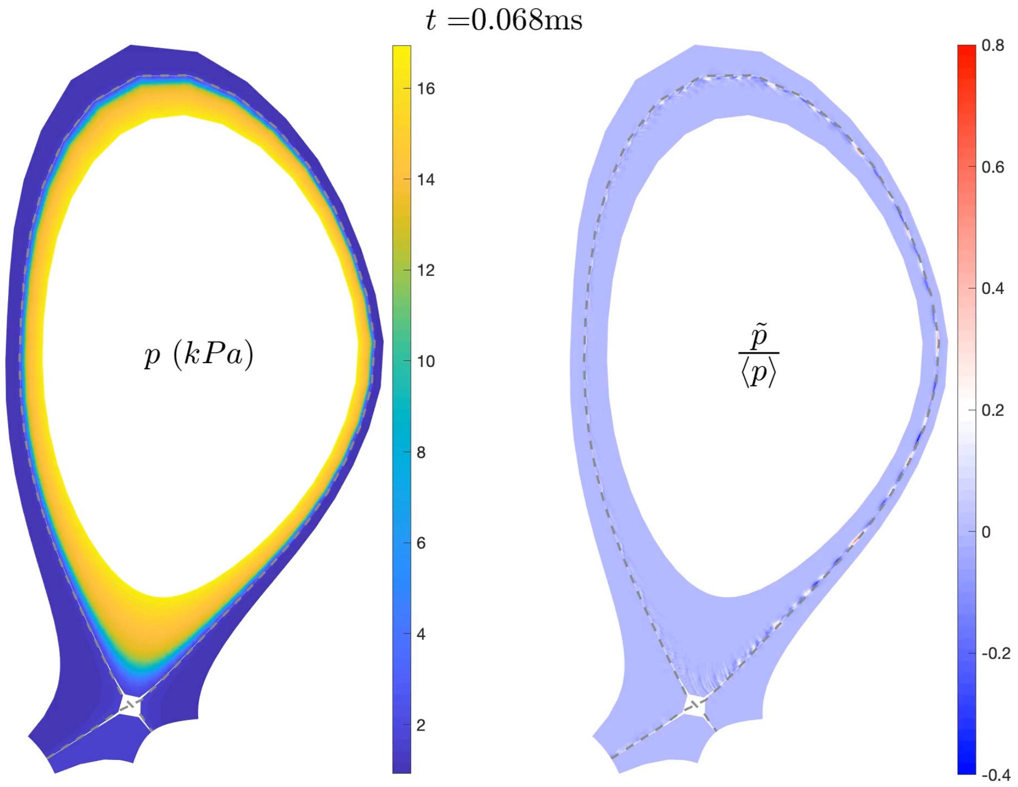
Quasi-coherent structure at near SOL (n=15)

Increased amplitude but no significant broadening

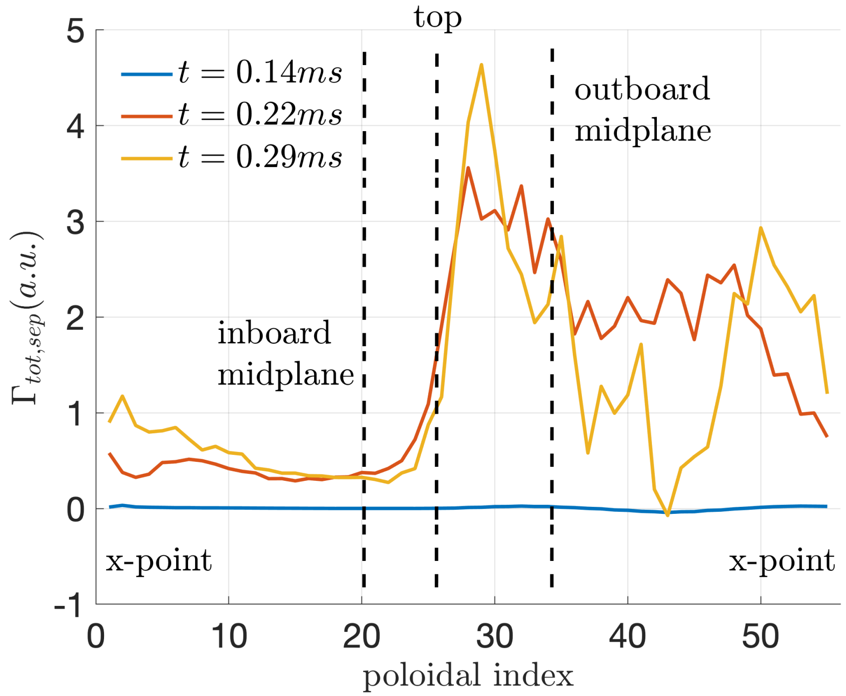
Helical striation pattern appears at far SOL; while near SOL still quasi-coherent

Striation pattern extends to near SOL

Enhanced instabilities and turbulence are developed

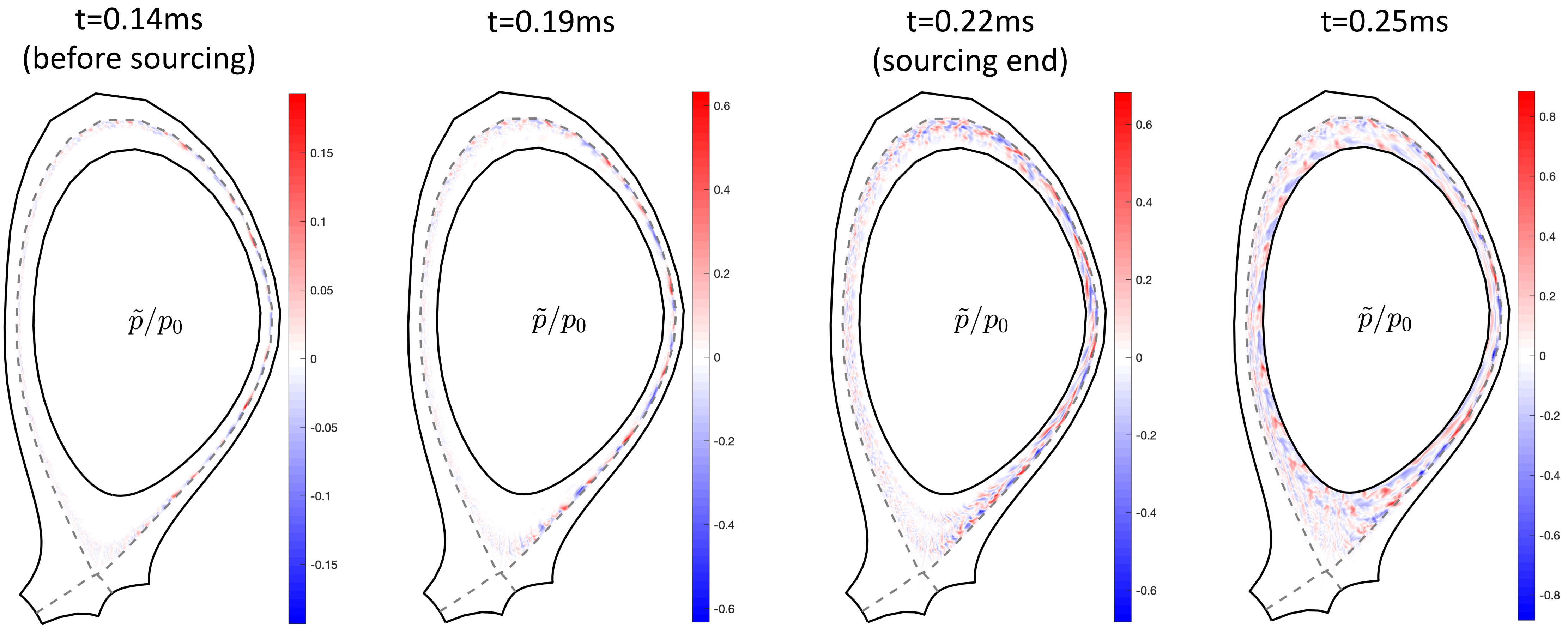


Pressure perturbation increases ~6x and spreads from near separatrix to the entire domain.



Radial heat flux across the separatrix (10us average) exhibits “ballooning” structure – >80% of total heat flux enters SOL from LFS.

Violent edge turbulence activity once TQ onsets


t=0.14ms
(before sourcing)

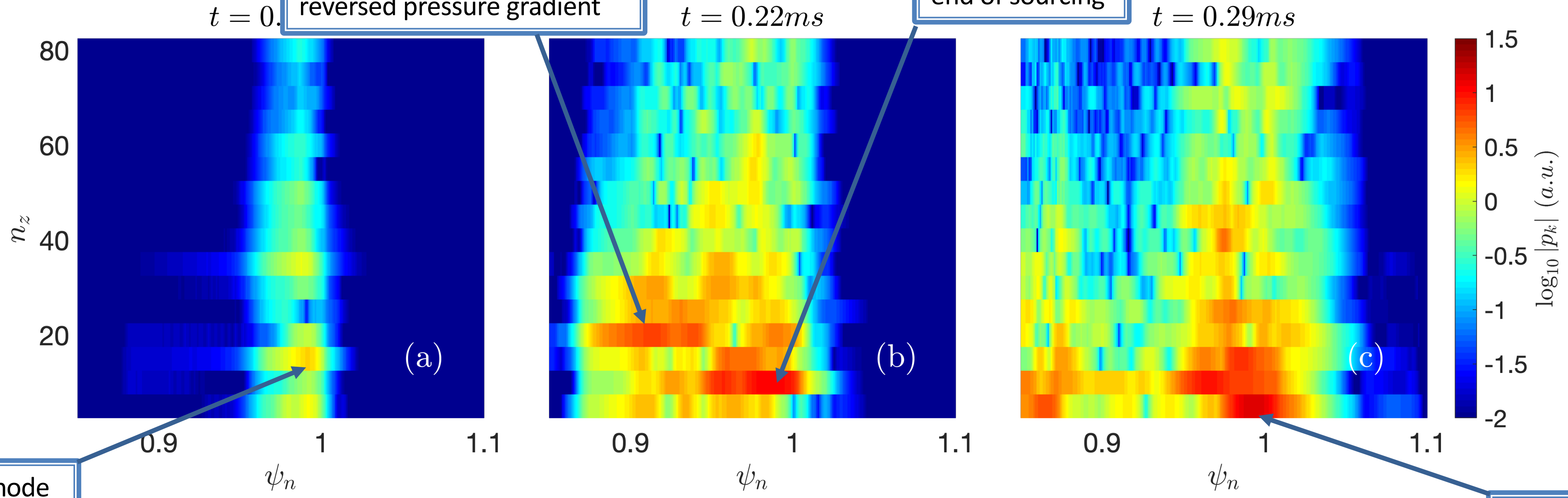
t=0.19ms

t=0.22ms
(sourcing end)

t=0.25ms

- ~6x increase in fluctuation level to O(1) in the pedestal region
- spreading from near separatrix to the entire domain

Evolution of toroidal mode spectrum



This n=20 mode corresponds to the instability occurs at inboard side due to the reversed pressure gradient

n=10 mode becomes dominant at the end of sourcing

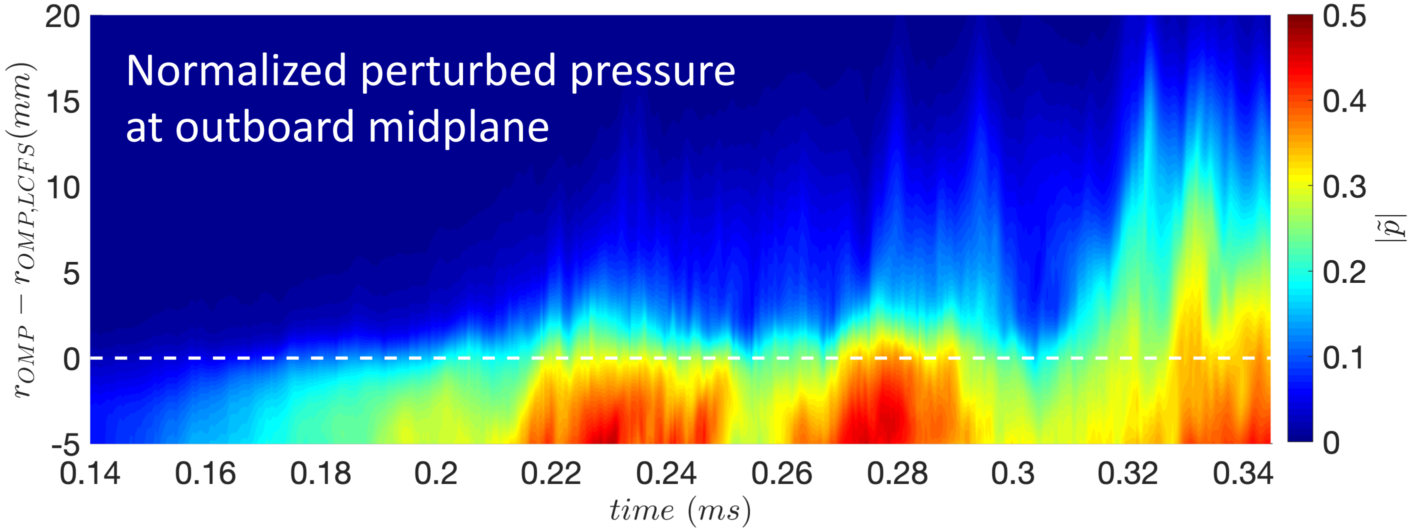
n=15 mode dominates prior TQ

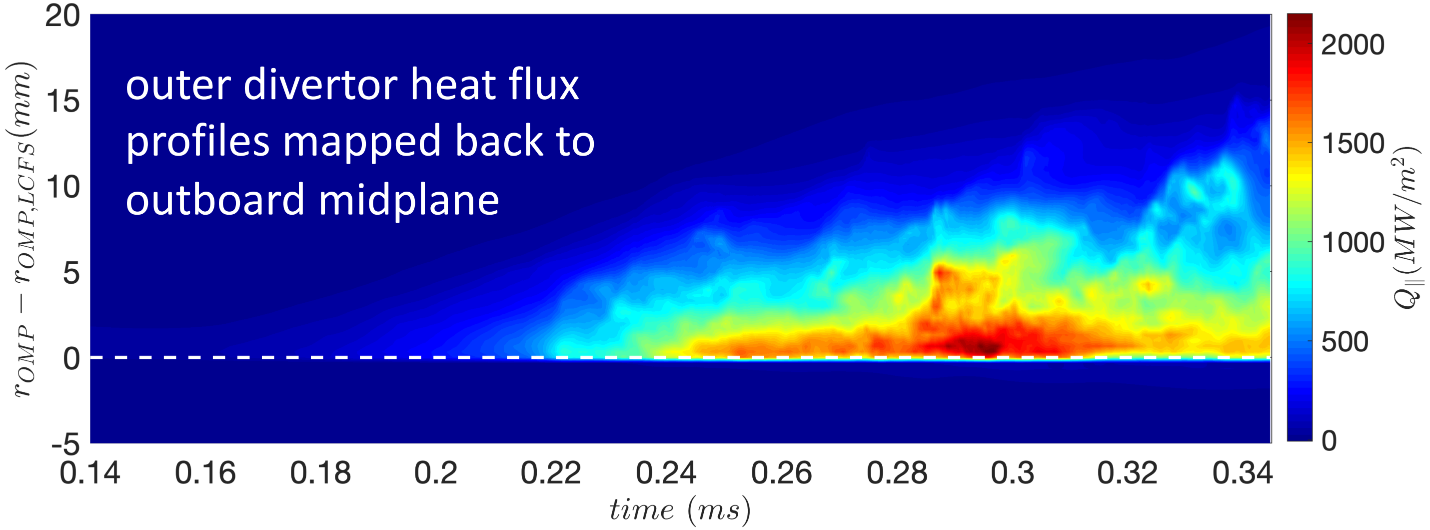
Dominant mode number further lowers to n=5

Toroidal mode number analysis of normalized pressure perturbation at the outboard mid-plane at (a) the beginning, (b) the end of energy injection, and (c) the peak of heat load.

- Dominant mode shifts to lower-k, i.e., larger eddies that are more resilient to shear
- Turbulence spreading also occurs in k-space

Outer divertor heat load correlated with OMP turbulence





45us lag suggests that divertor heat load is largely influenced by electron parallel heat conduction.

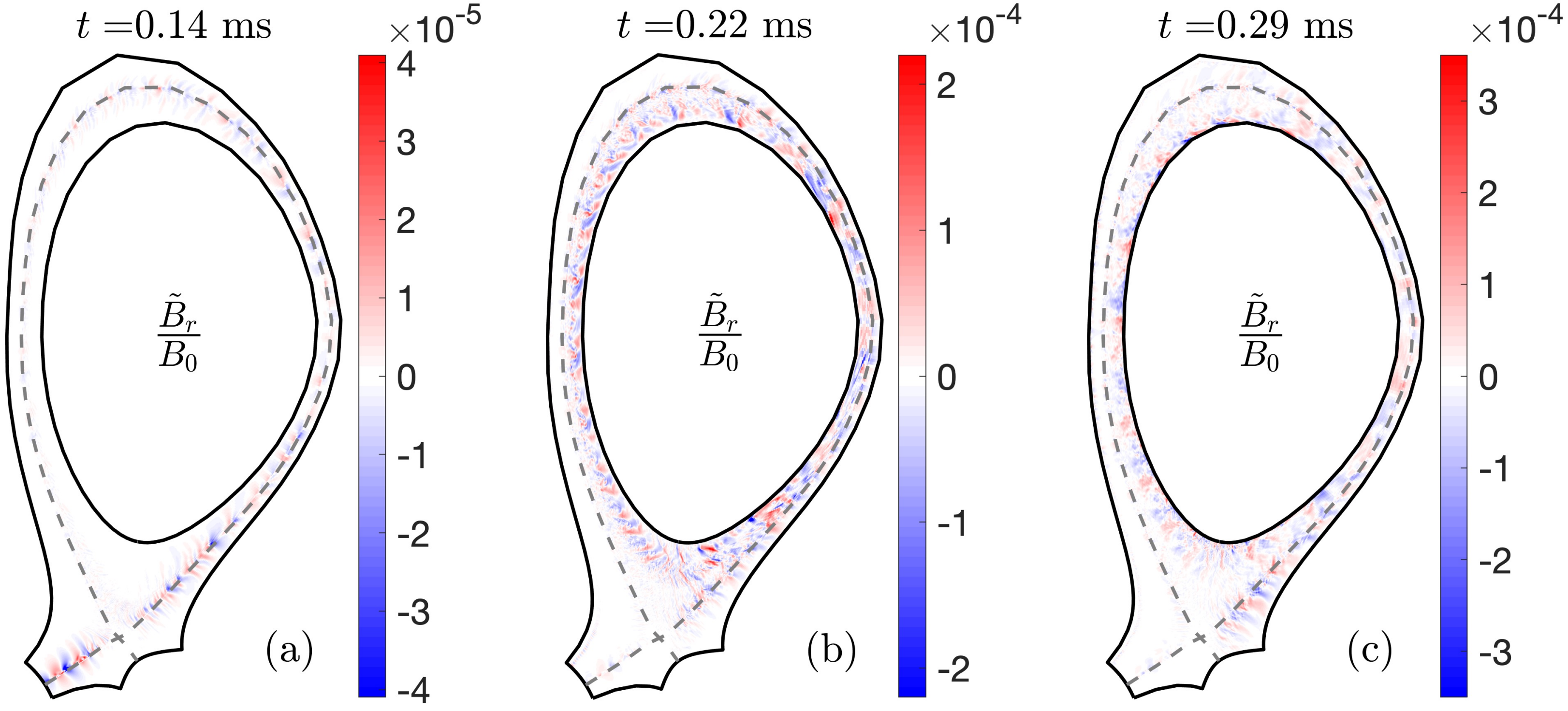
$$L = 16m,\ c_s = 2\times 10^5 m/s$$
$$v_{th,e} = 5\times 10^6 m/s$$
$$\kappa_{\|}^{e} \simeq 3\times 10^6 m^2/s$$
$$t_{conv} = 2L/c_s \simeq 160\mu s$$

$$\boxed{\begin{aligned} t_{cond,e} &= L^2/\kappa_{\|}^{e} \simeq 85\mu s \\ t_{fs,e} &= L/v_{th,e} \simeq 3\mu s \end{aligned}}$$

The classical HD scaling[1] is no longer valid for this over-driven system.
An example of λ_q scaling transits from drift to turbulence dominated regime[2].

[1] ***Goldston, Nucl. Fusion (2011)***
[2] ***Xu et al, Nucl. Fusion (2019)***

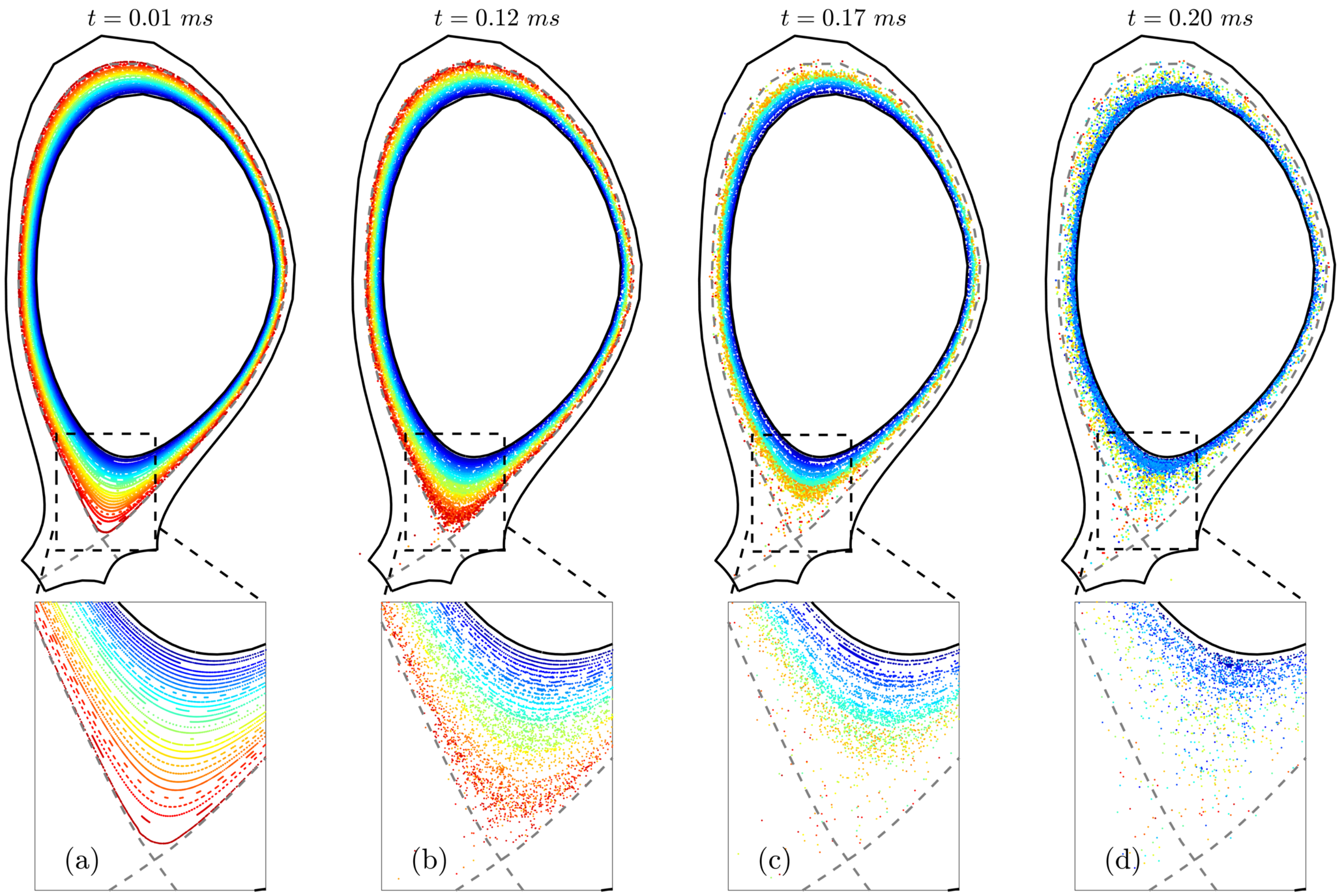
Order of magnitude increasing of magnetic fluctuation



Poloidal snapshots of radial component of perturbed magnetic field at (a) the beginning, (b) the end of energy injection, and (c) the peak of heat load.

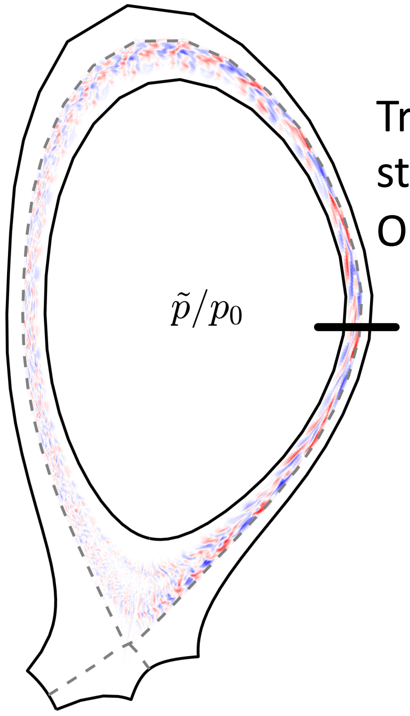
- Radial magnetic field perturbation increased for 10x to 10^{-4} level; and once again it spreads from near separatrix to the entire simulation domain.

Evolution of Poincaré plots

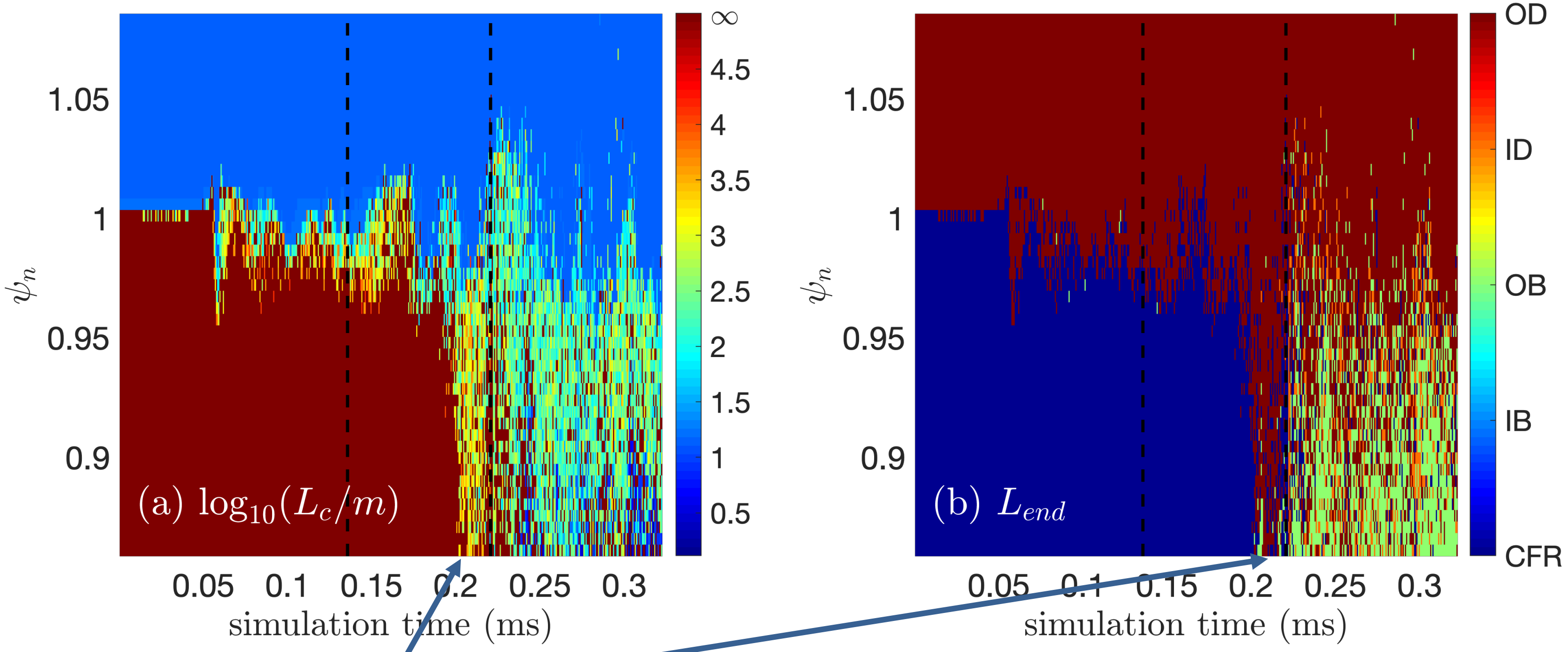


- Intact magnetic flux surface at the early linear stage
- Weakly stochastic layer near the separatrix but most of the inner closed flux surfaces are still closed (e.g., normal BOUT++ turbulence runs)
- Inner magnetic flux surfaces start to break down as the magnetic perturbation enhances
- Almost completely broken magnetic flux surfaces

Temporal evolution of OMP magnetic field-lines



Tracing starts at OMP

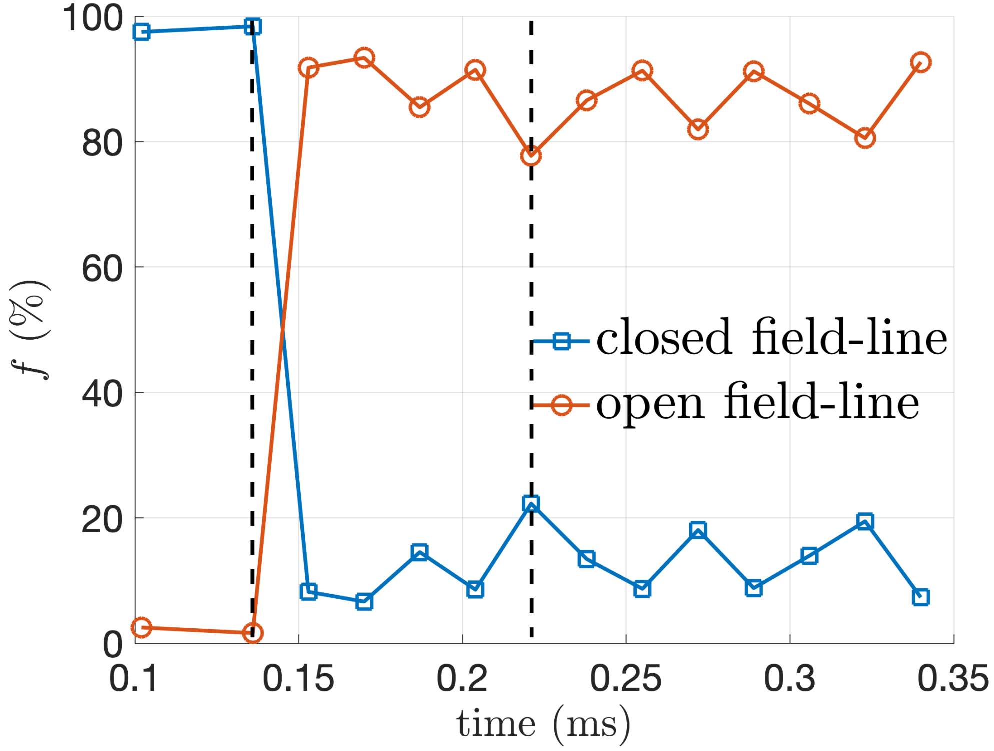


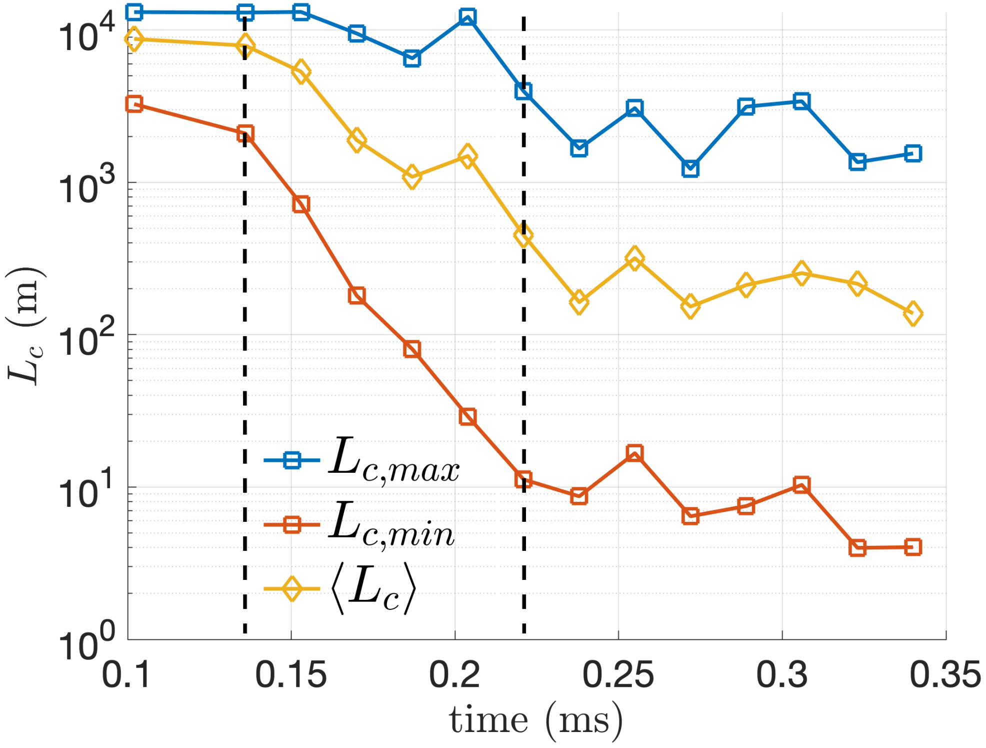
Around t=0.2ms, inner magnetic flux surfaces are completely destroyed; pedestal top can directly connect to divertor target plate!

CFR: closed flux region;
IB/OB: outer/inner boundary;
ID/OD: outer/inner divertor target

Pedestal top region directly connects to PFC in TQ

Tracing 3564 field-lines uniformly distributed along field-line and toroidal directions on psin=0.95 surface



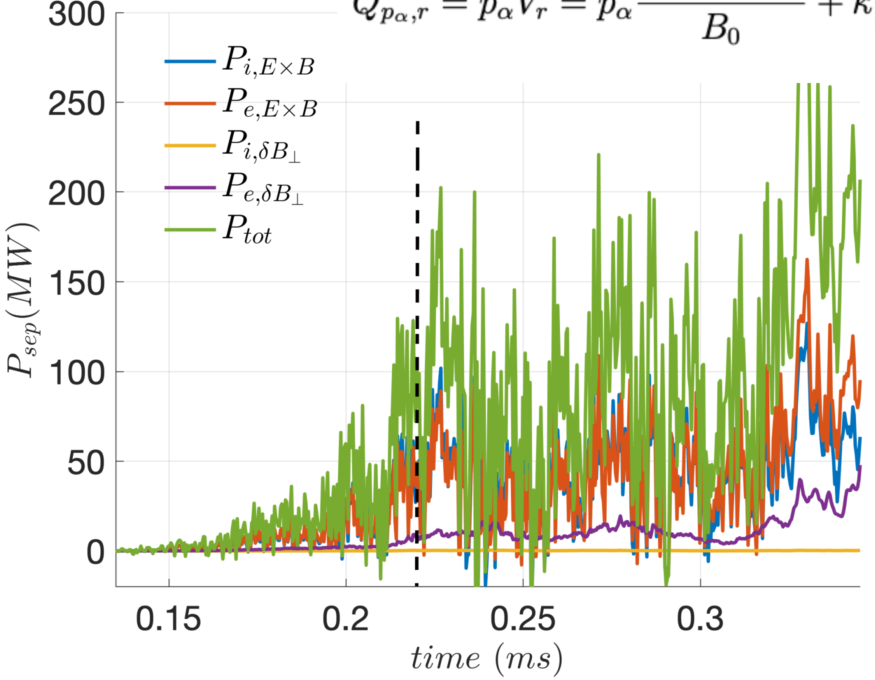


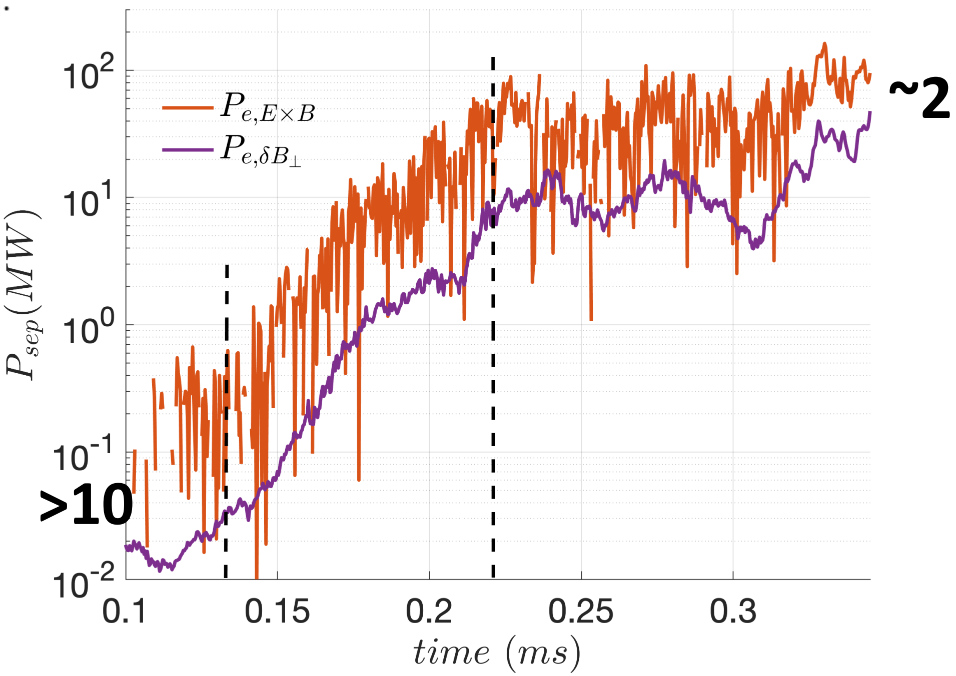
- Psin=0.95 surface breaks shortly after TQ onsets and won't heal.

- Magnetic connection length (open field-lines) decreases as stochasticity increases

Contributions of power across the separatrix

$$Q_{p_\alpha,r} = p_\alpha V_r = p_\alpha \frac{(\vec{b}_0 \times \nabla\phi)_r}{B_0} + \kappa_{\parallel\alpha} \frac{\left(\vec{b}_0 \times \nabla A_\parallel\right)_r}{B_0} \cdot \nabla T_\alpha.$$



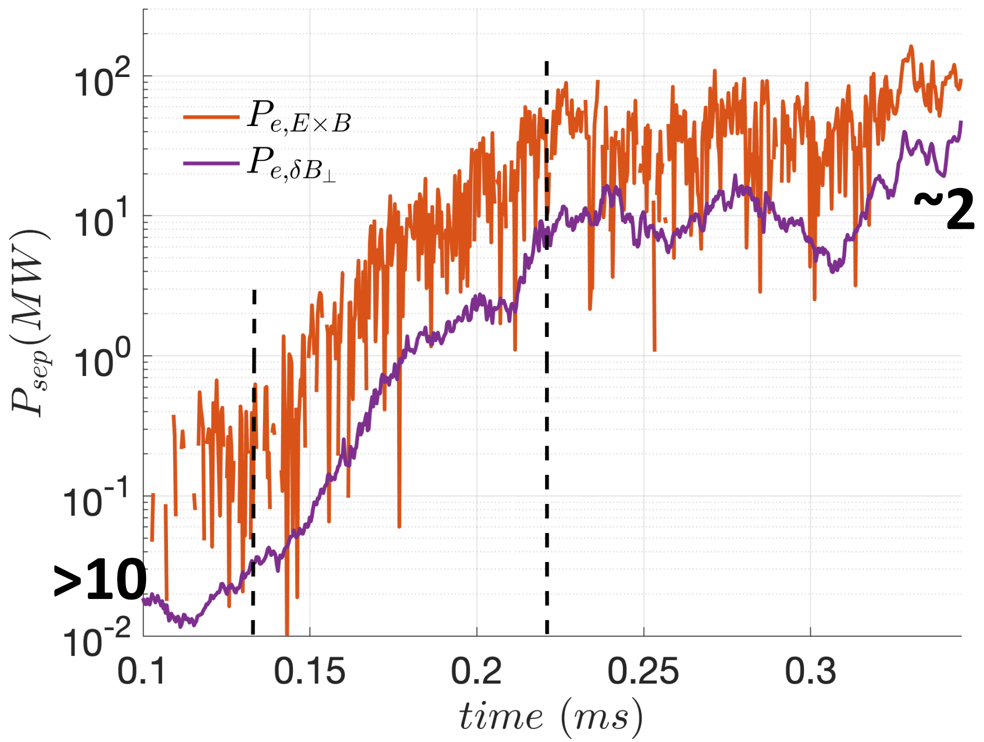


- Overall, turbulent ExB convection dominates electron and ion cross-field transport.
- EM effects has substantial influence on electrons (10~30%) but not much on ions.

- For electrons, EM effect becomes more important as the field stochasticity increases.
- The roles of ExB turbulent transport and flutter contribution is case- and time- dependent

Stochastic field has limited impact on particle transport

$$\Gamma_{n,r} = nV_r = n\frac{(\vec{b}_0 \times \nabla\phi)_r}{B_0} + nV_{\parallel i}\frac{\left(\vec{b}_0 \times \nabla A_{\parallel}\right)_r}{B_0}.$$



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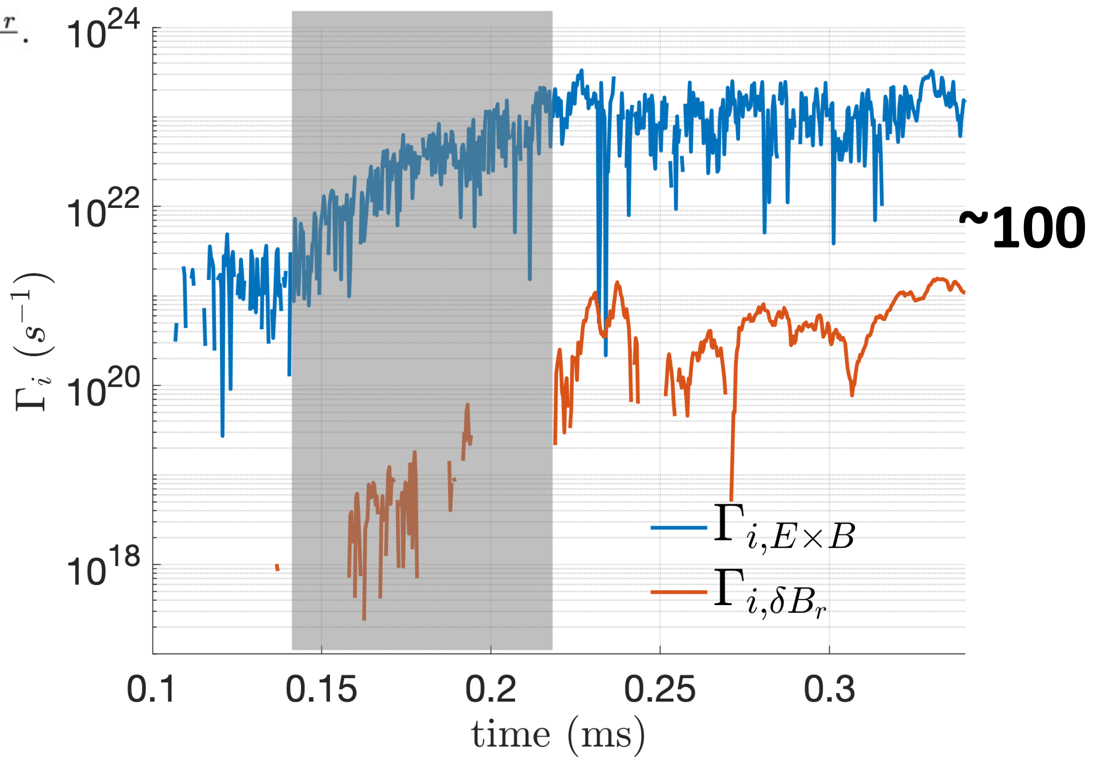

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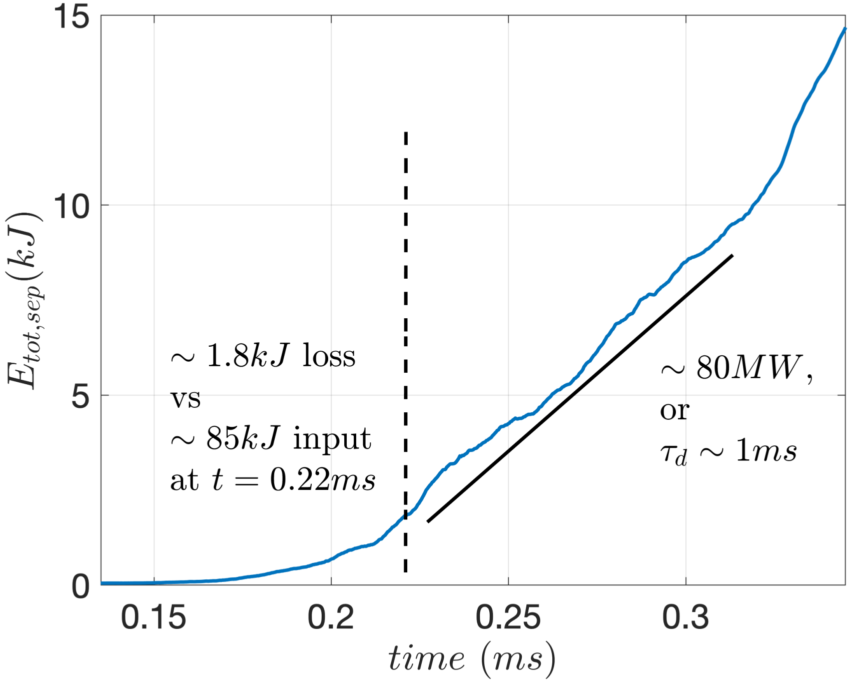
- Advection vs conduction
- Ions are heavy

Estimate of energy deposition time

Approach 1: radial energy outflow rate

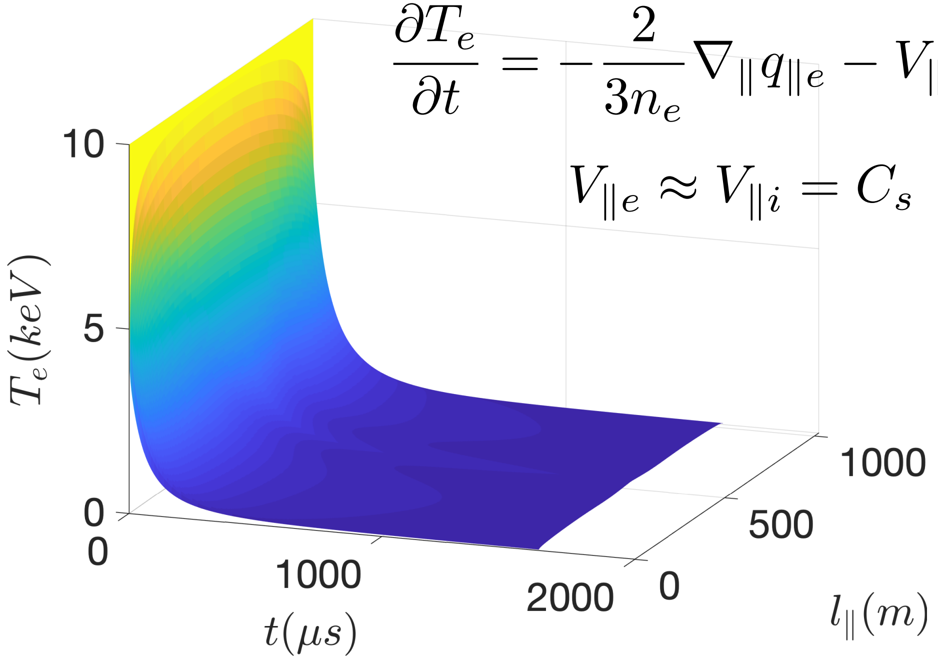


- only a few percent of injected energy across separatrix during TQ
- 85kJ injected energy takes ~1ms to be radially transported and deposited to divertor

Approach 2: 1D parallel thermal decay

$$\frac{\partial T_e}{\partial t} = -\frac{2}{3n_e}\nabla_{\|} q_{\|e} - V_{\|e}\nabla_{\|} T_e$$

$$V_{\|e} \approx V_{\|i} = C_s$$



- exponential decay $T \propto \exp(-t/\tau)$ with $\tau \propto L_{\|}/T_{e0}^{1/2}$
- for $L_{\|} = 1000\ m, T_{e0} = 1\ keV$
  $\rightarrow \tau = 0.25 \sim 0.8\ ms$

Summary

- BOUT++ TQ simulation observed signatures in agreement with experiments: surge of divertor heat load and edge temperature; broadening of heat flux width; prolonged energy deposition time; …
- Elevated pedestal pressure excites low-n ballooning-type instability/turbulence
  - Enhances radial heat transport across the entire domain significantly;
  - Determines downstream divertor heat load (i.e., drift->turbulent scaling)
- **Large magnetic fluctuation (10^{-4}) results in stochastic magnetic field-lines that contributes to electron radial heat transport (10~30% of total heat flux across the separatrix) and heat flux width broadening (at the later stage)**

Thank you for listening!