P1-23

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Simulation Study on Impact of Pedestal Height on Energy Loss Process with Resistive Ballooning Turbulence during Pedestal Collapse

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in collaboration with

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Background: roles of $n=0$ perp. flows during ELM crash

It is one of key issues for fusion tokamak reactors to understand dynamics of edge localized modes (ELMs)

➡ Nonlinear MHD codes have been developed and given qualitative understandings on nonlinear dynamics of ELMs and ELM controls

Previous studies on $n=0$ perpendicular flow during ELM crash
($m=0$: zonal flow (ZF), $m\neq0$: convective cells (CCs))

- Suppression of energy loss [JOREK, Huysmans+ NF'07, etc.]

  Sheared ZF and CCs suppress radial transport of density filaments

  ✓ ZF and CCs generated by residual of MHD force balance

- Enhancement of energy loss [BOUT++, Jhang+ NF'16]

  Subsequent energy loss by ZF driving Kelvin-Hemlmholz instability

  ✓ ZF generated by residual of flow stress (Reynolds/gyro-viscous)

BOUT++ has been improved for n=0 net flow generation

BOUT++ [1] employ a dual coordinate system consisting of flux-surface and field-aligned coordinates for tokamak edge MHD sims.

- Describing resonant mode structure efficiently
- Flute-ordered ($k_\parallel$=0) 1D-Poisson solver in radial direction

  ➡ n=0 force balance between $J\times B$ force and pressure during pedestal collapse described in ($m\neq0,n=0$) vorticity equation is removed

n=0 2D Poisson solver [2] has been introduced in BOUT++ ELM module for n=0 net flow and magnetic field generation [3]

✓ZF/CCs driven by residual of MHD force balance and flow stress

✓n=0 magnetic field balancing with deformed pressure during pedestal collapse

[1] Dudson+ CPC'09, [2] Dudson+ PPCF'17, [3] Seto+ PoP'19

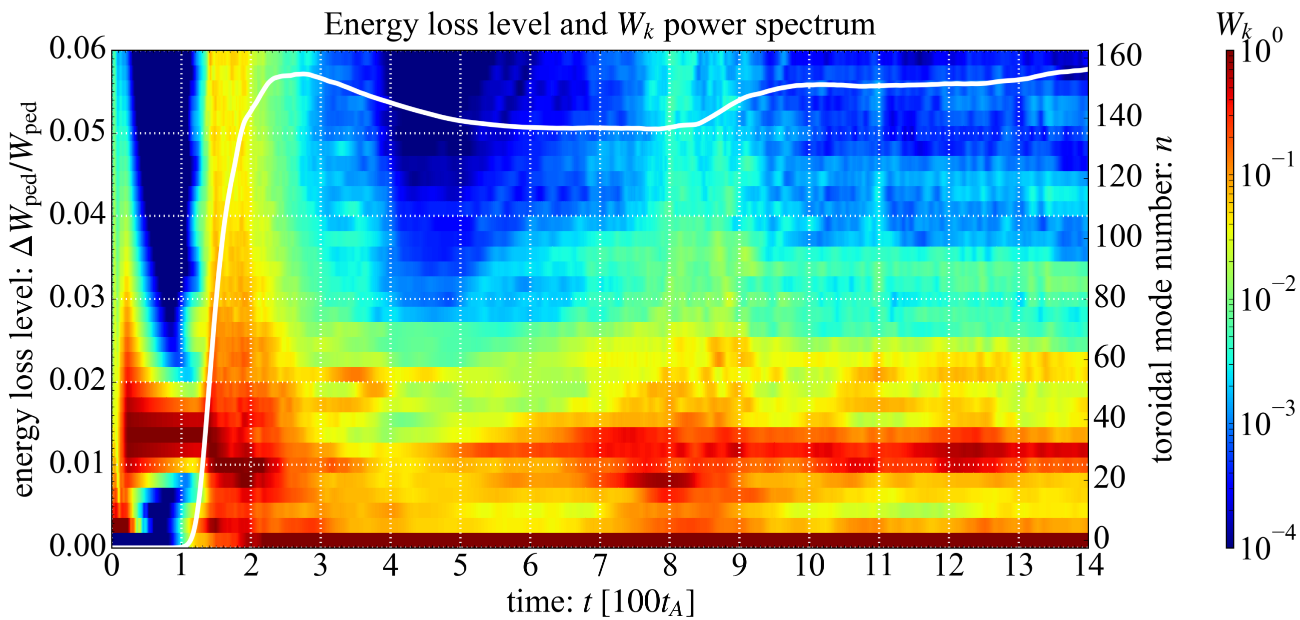
QST

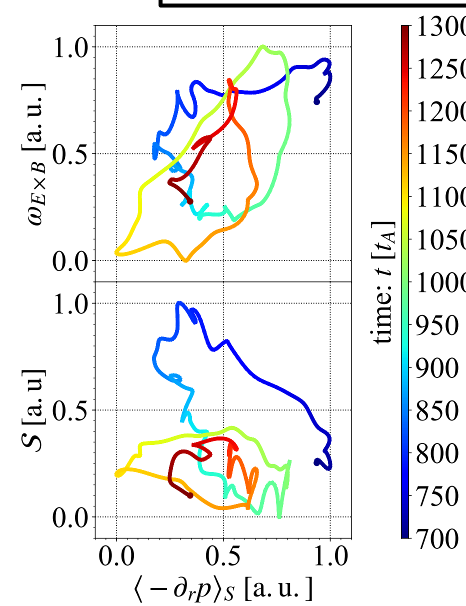
Motivation of this research

Improved BOUT++ successfully captures

- Suppression of energy loss level by strongly sheared ZF/CCs
- Enhancement of energy loss level by a secondary instability driven by damped oscillations

Seto+ PoP’19





This work is however limited to a sim. with one parameter set

➡ A sensitivity analysis on energy loss level during pedestal collapse with RBM turbulence against pedestal height is reported

Scale-separated four-field RBM/DW model

$$\frac{\partial \varpi_1}{\partial t} = -\left[F_0, \varpi_1\right] - \left[F_1, \varpi_0 + \varpi_1\right] + \mathcal{G}\left(p_0, F_1\right) + \mathcal{G}\left(p_1, F_0 + F_1\right)$$
$$-B_0 \partial_\parallel \left(\frac{J_{\parallel 1}}{B_0}\right) + B_0 \left[A_{\parallel 1}, \frac{J_{\parallel 0} + J_{\parallel 1}}{B_0}\right] + \frac{\boldsymbol{b}_0 \times \boldsymbol{\kappa}_0 \cdot \nabla_\perp p_1}{B_0} + \mu_\parallel \partial_\parallel^2 \varpi_1 + \mu_\perp \nabla_\perp^2 \varpi_1$$

$$\frac{\partial A_{\parallel 1}}{\partial t} = -\partial_\parallel \phi_1 + \left[A_{\parallel 1}, \phi_1\right] + \delta_{\mathrm{e}} \partial_\parallel p_1 - \delta_{\mathrm{e}} \left[A_{\parallel 1}, p_0 + p_1\right] + \eta J_{\parallel 1} - \lambda \nabla_\perp^2 J_{\parallel 1}$$

$$\frac{\partial p_1}{\partial t} = -\left[\phi_1, p_0 + p_1\right] + \chi_\parallel \partial_\parallel^2 p_1 + \chi_\perp \nabla_\perp^2 p_1$$
$$-2\beta_* \left[\frac{\boldsymbol{b}_0 \times \boldsymbol{\kappa}_0 \cdot \nabla_\perp \phi_1}{B_0} + B_0 \partial_\parallel \left(\frac{v_{\parallel 1} + d_{\mathrm{i}} J_{\parallel 1}}{2B_0}\right) - B_0 \left[A_{\parallel 1}, \frac{v_{\parallel 1} + d_{\mathrm{i}} J_{\parallel 1}}{2B_0}\right]\right]$$

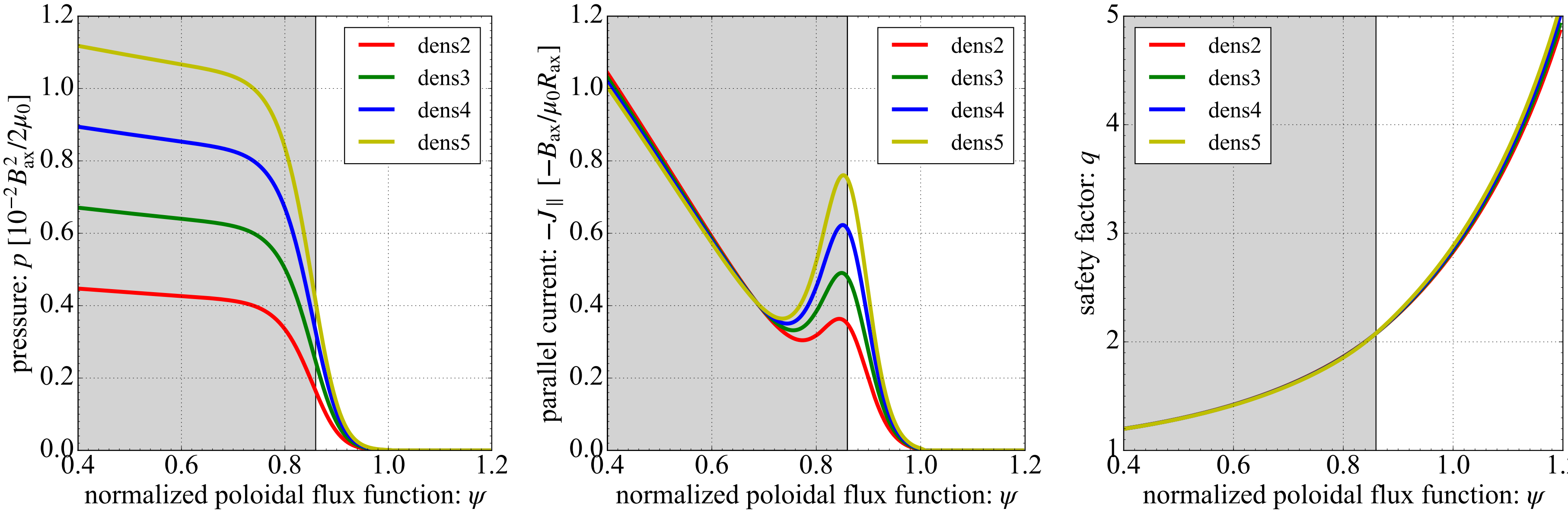
$$\frac{\partial v_{\parallel 1}}{\partial t} = -\left[\phi_1, v_{\parallel 1}\right] - \frac{1}{2} \partial_\parallel p_1 + \frac{1}{2}\left[A_{\parallel 1}, p_0 + p_1\right] + \nu_\perp \nabla_\perp^2 v_{\parallel 1}$$

$$F = \phi + \delta_{\mathrm{i}} p, \quad \varpi = \nabla\left(\cdot \frac{\nabla_\perp F}{B_0^2}\right), \mathcal{G}(f, g) = \frac{\delta_i}{2}\left\{\left[f, \nabla \cdot \left(\frac{\nabla_\perp g}{B_0^2}\right)\right] + \left[g, \nabla \cdot \left(\frac{\nabla_\perp f}{B_0^2}\right)\right] + \nabla \cdot \left(\frac{\nabla_\perp [f, g]}{B_0^2}\right)\right\}$$

- Simplified by following approximations
  - ✓ Boussinesq approximation
  - ✓ Constant dissipations and ion number density
  - ✓ Equilibrium E_{r} is excluded
- A set of complete set of energy channels

$$n_{\mathrm{i}} = 1 \times 10^{19} [\mathrm{m}^{-3}]$$
$$\mu_\parallel = \chi_\parallel = 1 \times 10^{-1}$$
$$\mu_\perp = \chi_\perp = \nu_\perp = 1 \times 10^{-7}$$
$$\eta = 1 \times 10^{-8}$$
$$\lambda = 1 \times 10^{-12}$$

A Set of Shifted Circular Equilibria (R_{ax}≃3.5[m], B_{ax}≃2.0 [T], A≃2.8)



- 1/5th-annular wedge torus domain with N_ψ=1024, N_y=64,N_ζ=128 and up to 32nd harmonics (n=0, 5, 10…, 160) are taken into account

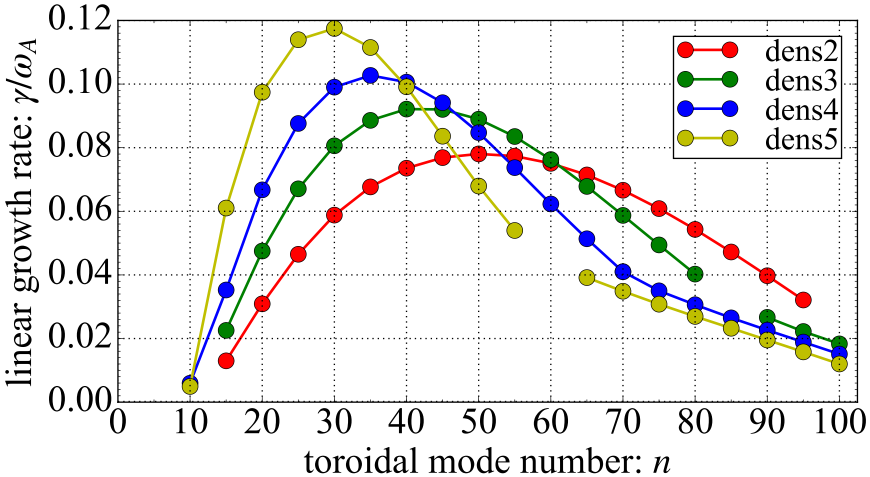
  ➡high-n modes are introduced as an energy sink

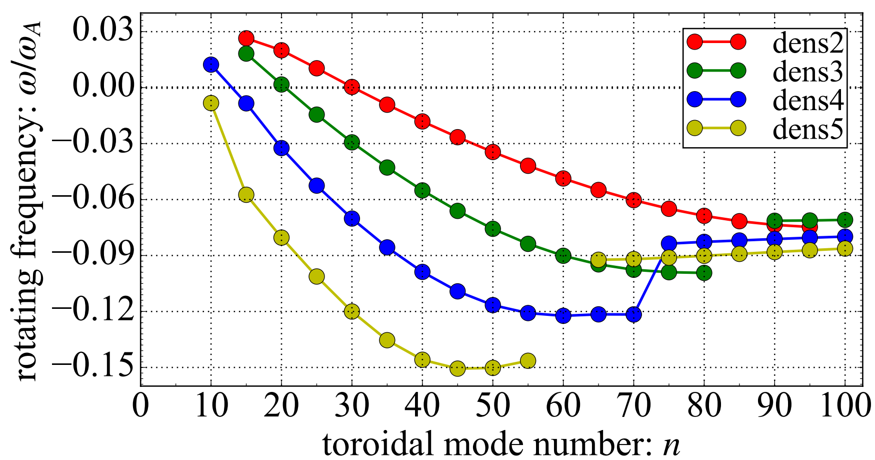
- Energy loss released from shaded region: $\Delta W_{ped}/W_{ped}$

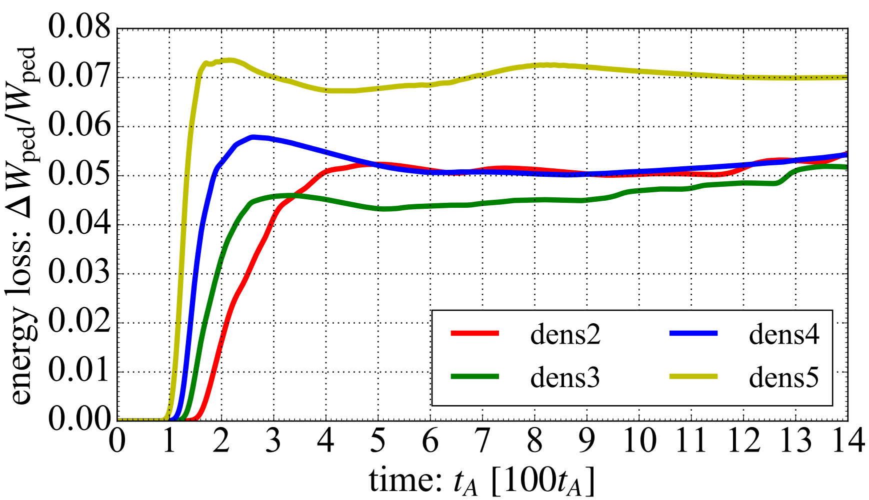
$$\Delta W_{\rm ped} = -\int_{V_{\rm ped}} p_1 dV,\ \ W_{\rm ped} = \int_{V_{\rm ped}} p_0 dV,$$

Note: dens4 with N_ψ=1536, N_y=64,N_ζ=128 is employed in Seto+PoP’19

Linear stabilities against four-field model and energy losses



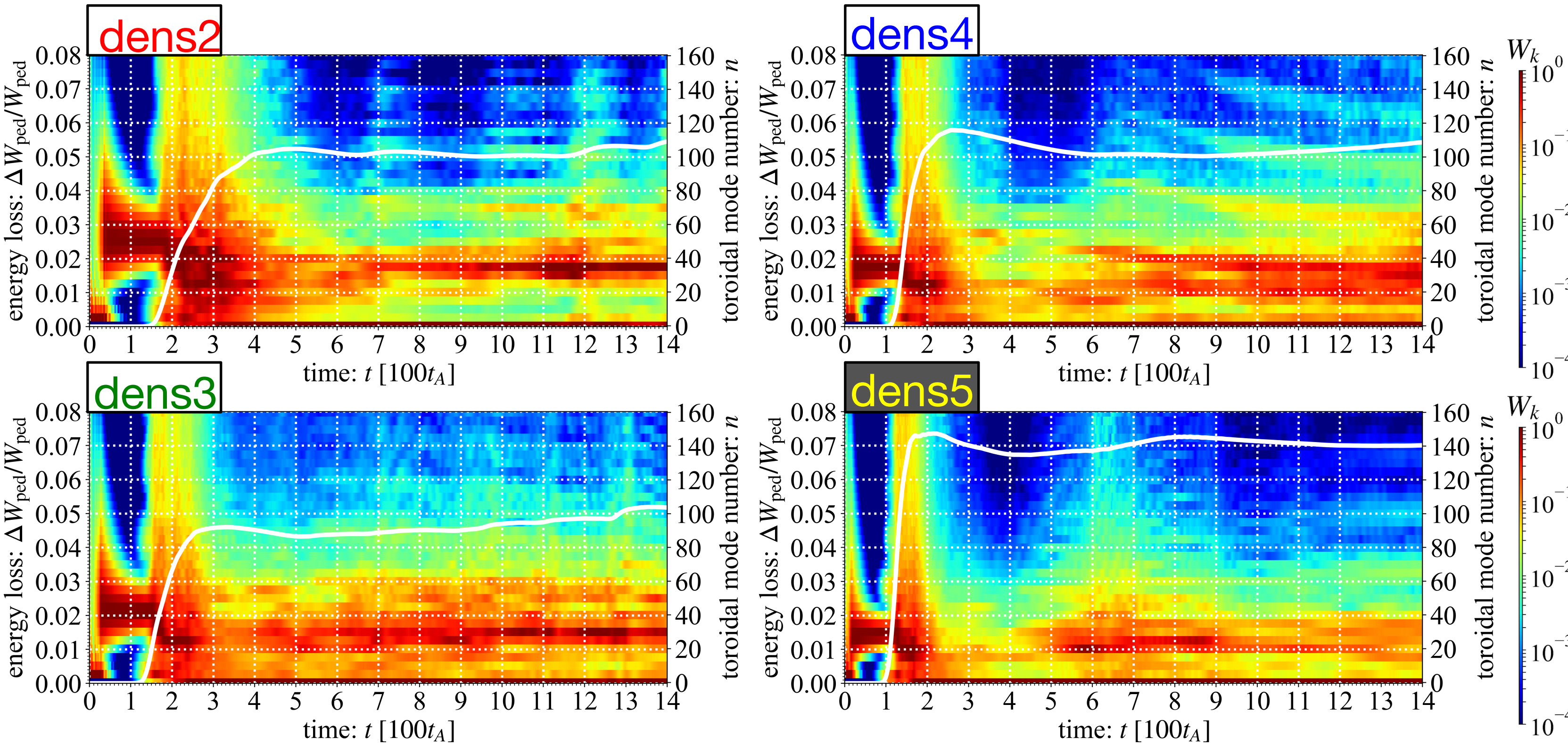




Note: simulated time in SI unit
$1400t_{\mathrm{A}} \sim 5\times10^{-4}$ [s]

- Most unstable mode shifts to low-n region with pedestal height
- High-n modes are destabilized by current compression [Rhee+ PoP'17]
- Energy losses of dens2, dens3 and dens4 are comparable at t=$1400t_{\mathrm{A}}$
- Energy loss of dens5 is larger than those of the others by 40%

Energy loss level is related to perp. kinetic energy spectrum



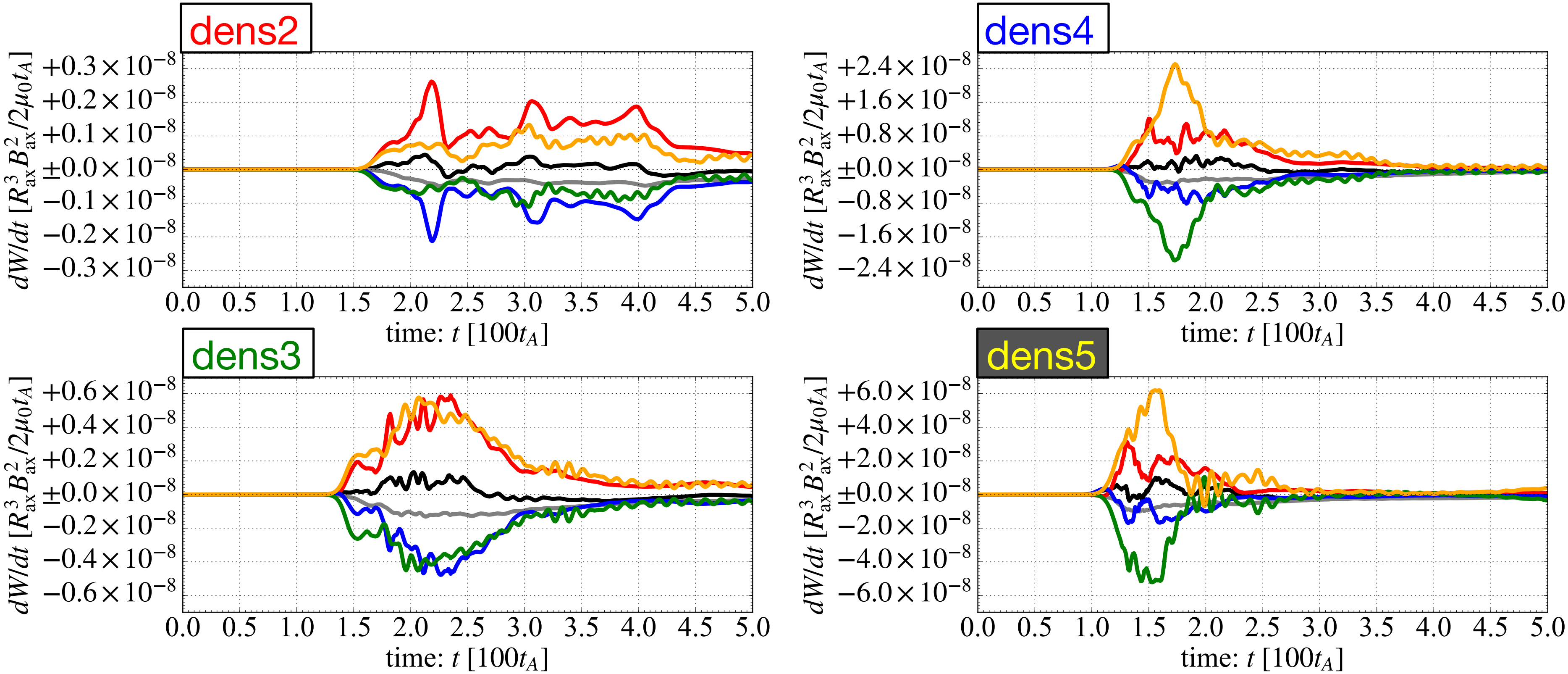
- Energy loss increases during subsequent energy cascades in dens2 and dens3
- Energy loss doesn't increase during small energy cascade (t~$700t_A$) in dens4
- Energy loss gets saturated after a small energy cascade in dens5

perp. kinetic energy: W_k

$$W_k = \int_V \frac{|\nabla_\perp F_1|^2}{2B_0^2} dV$$

V: volume of whole domain

Breakdown of transfer rate of n=0 perp. kinetic energy

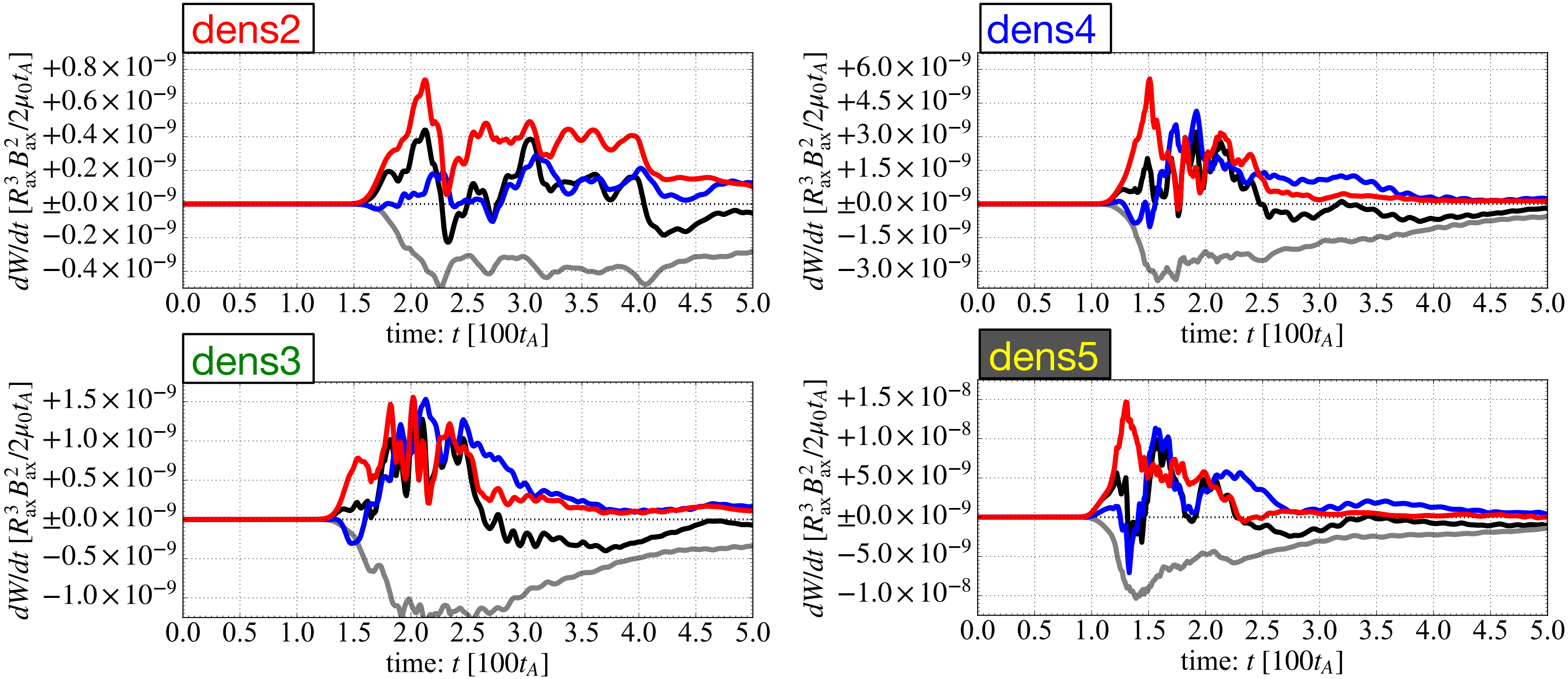


- Flow stresses are stronger than MHD forces in dens2 (most stable)
- MHD forces increase with pedestal height and become dominant in dens4 and dens5

$$\frac{\partial W_k}{\partial t} = T_{k,R} + T_{k,ID} + T_{k,J\times B} + T_{k,C} + T_{k,D}$$

- Reynolds stress
- Ion gyro-vis. stress
- $J\times B$ force
- toroidal curvature
- loss by dissipation

n=0 net flow generation during the pedestal collapse

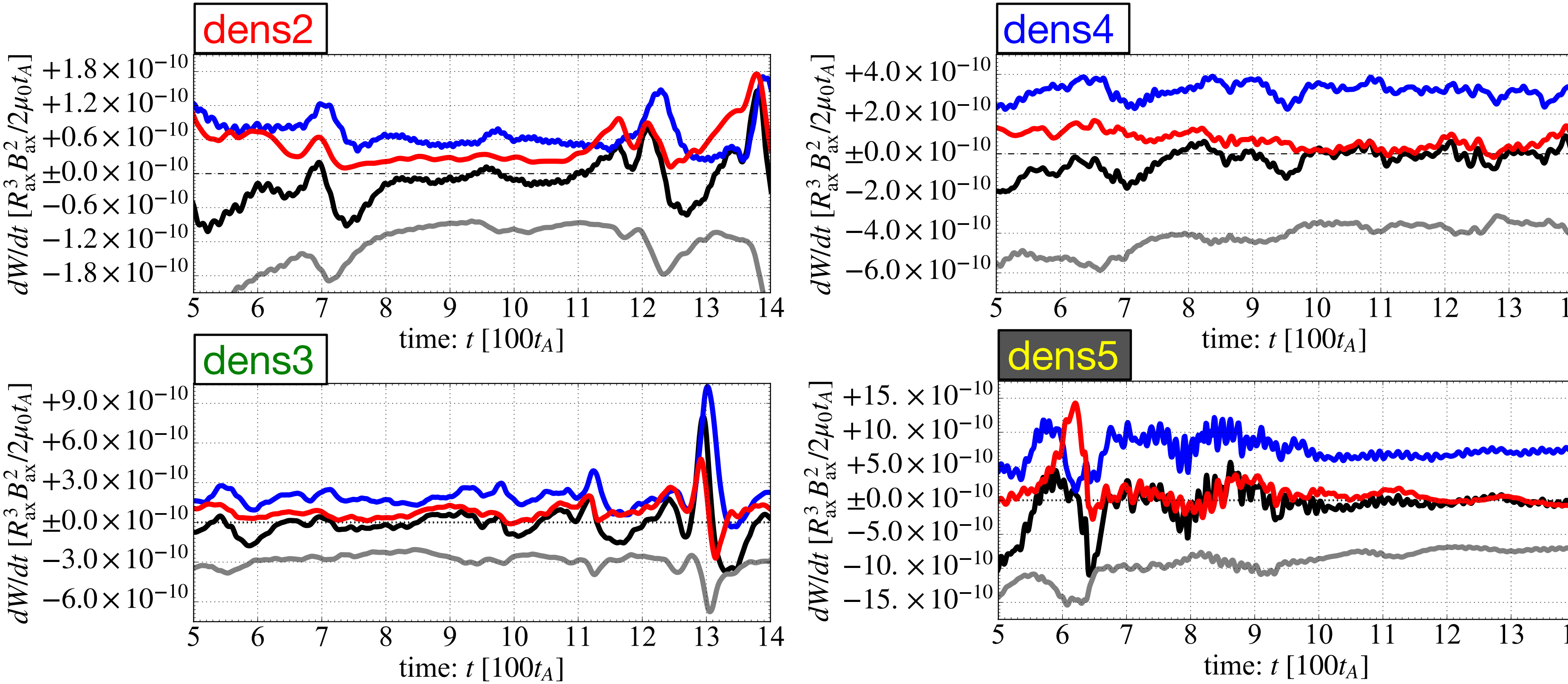


- Residual of flow stress increases at early phase in the pedestal collapse
- Residual of MHD force increases after the pedestal collapse with pedestal height

$$\boxed{\frac{\partial W_k}{\partial t}} = \boxed{T_{k,R} + T_{k,ID}} + \boxed{T_{k,J\times B} + T_{k,C}} + \boxed{T_{k,D}}$$

- Residual of flow stress
- Residual of MHD force
- loss by dissipation

n=0 net flow generation after the pedestal collapse

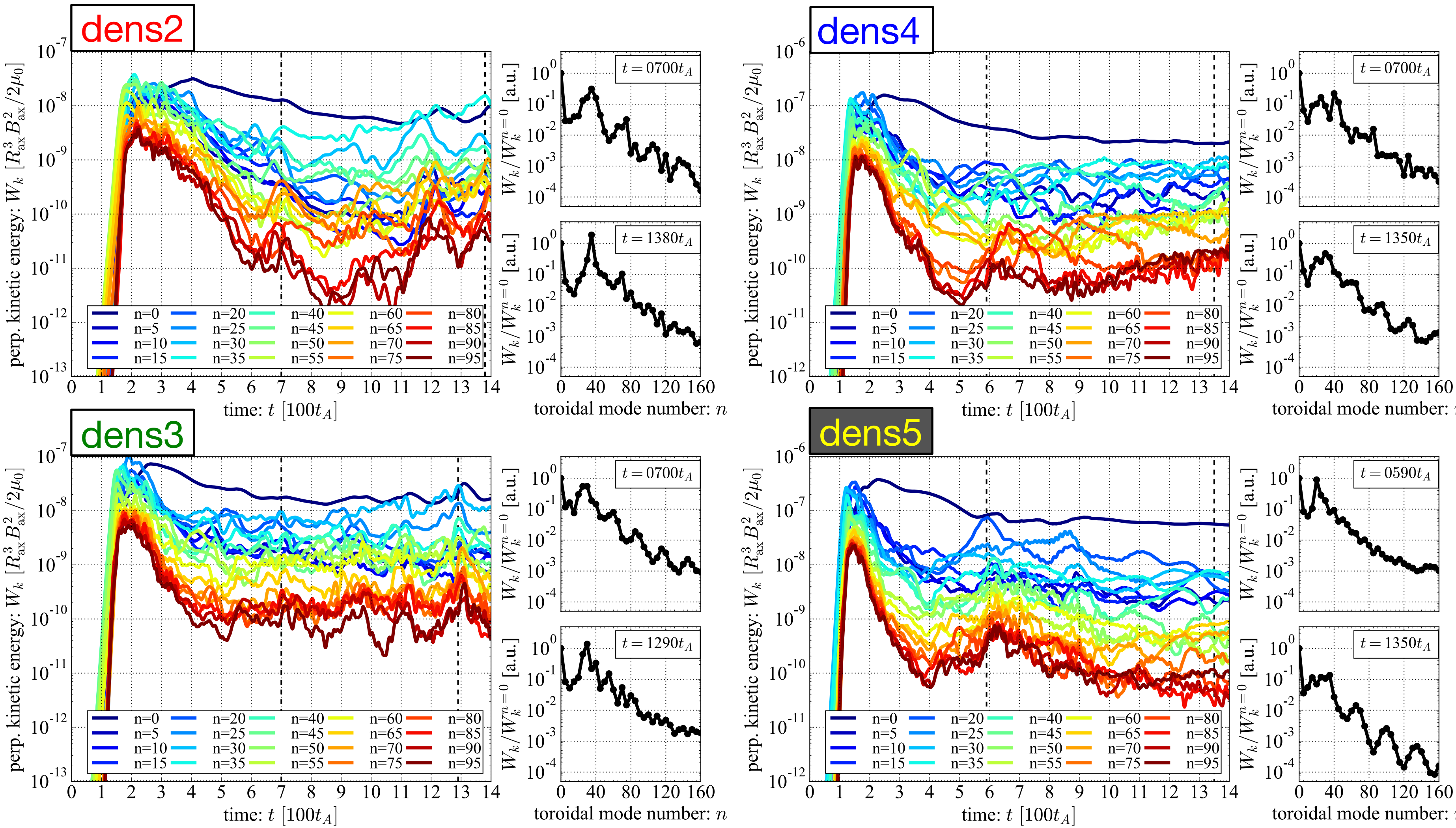


- n=0 net flow is sustained by residual of MHD force in all cases
- Residual of flow stress increases prior to that of MHD force during energy cascade in dens2 & dens3

$$\boxed{\frac{\partial W_k}{\partial t}} = \boxed{T_{k,R} + T_{k,ID}} + \boxed{T_{k,J\times B} + T_{k,C}} + \boxed{T_{k,D}}$$

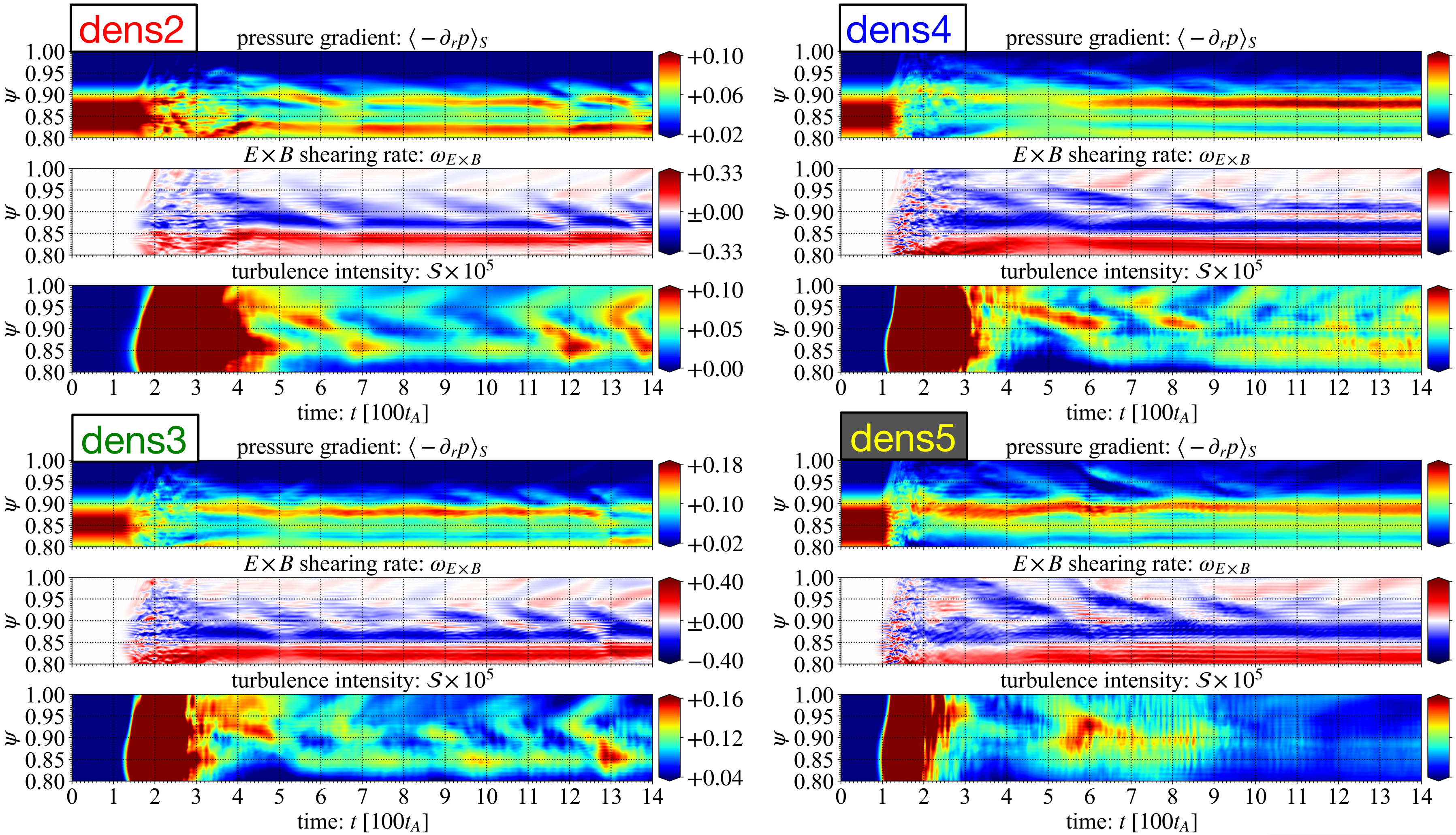
- Residual of flow stress
- Residual of MHD force
- loss by dissipation

Time evolution of toroidal mode spectrum of perp. kinetic energy



- Long-lived modes comparable to n=0 mode exist in dens2 and dens3
- n=20 mode temporary grows and damps in dens5

DOs between pressure and turbulence weaken with pedestal height

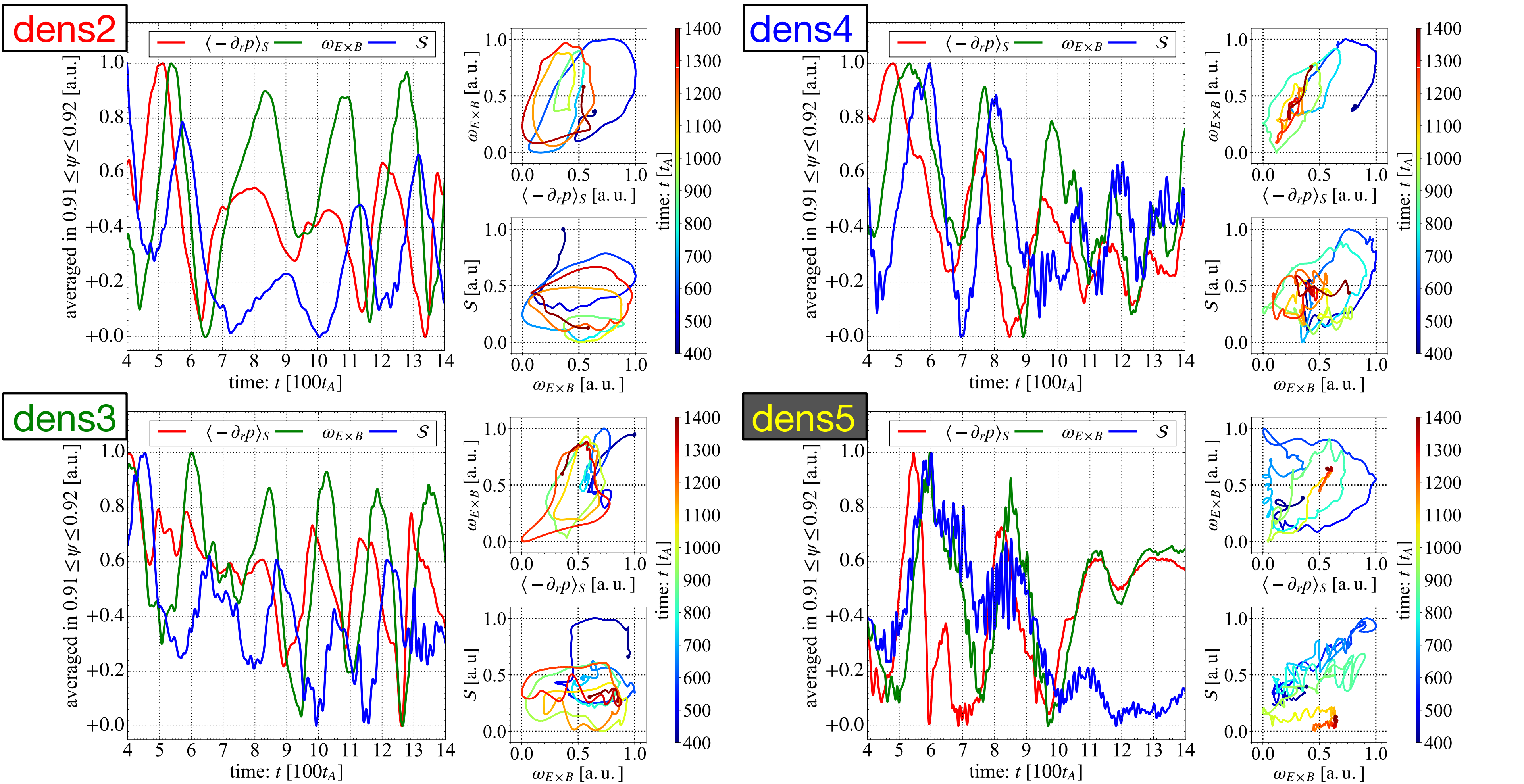


Damped oscillations (DOs) clearly appear in dens2, dens3 and dens4

➡DOs continue to small subsequent collapses in dens2 & dens3

$$\mathcal{S} = \sqrt{\sum_{n' \neq 0} |\phi_1^{n=n'}|^2}$$

Phase Diagrams in Outer Core Region after the Pedestal Collapse



- DOs between -∇p and $\omega_{E\times B}$ are observed in all cases
- DOs between $\omega_{E\times B}$ and S are observed in dens2, dens3 and dens4

➡ Bursty turbulence enhances energy transport in dens2 & dens3

Summary

Impact of pedestal height on energy loss process with RBM turbulence during/after pedestal collapse has been investigated

- **n=0 net flow generation**
  - ✓ driven by residual of flow stress and MHD force during the pedestal collapse
  - ✓ sustained mainly by residual of MHD force after the pedestal collapse

- **Interplay between n=0 $E\times B$ flow and turbulence**
  - ✓ DOs between pressure grad. and n=0 $E\times B$ flow exist in all cases
  - ✓ DOs between n=0 $E\times B$ flow and turbulence intensity are observed more clearly with decreasing pedestal height

    ➡ Bursty turbulence accompanied with DOs enhances non-local transport and increase energy loss level in dens2 & dens3