Island-Turbulence interactions and Role of Zonal Flows

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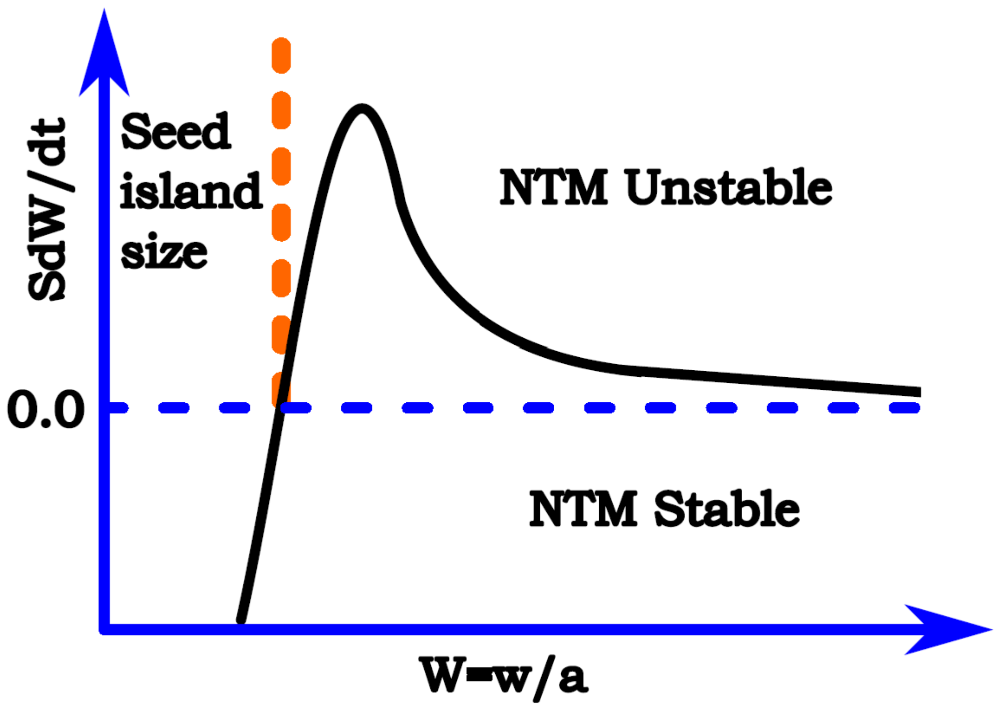
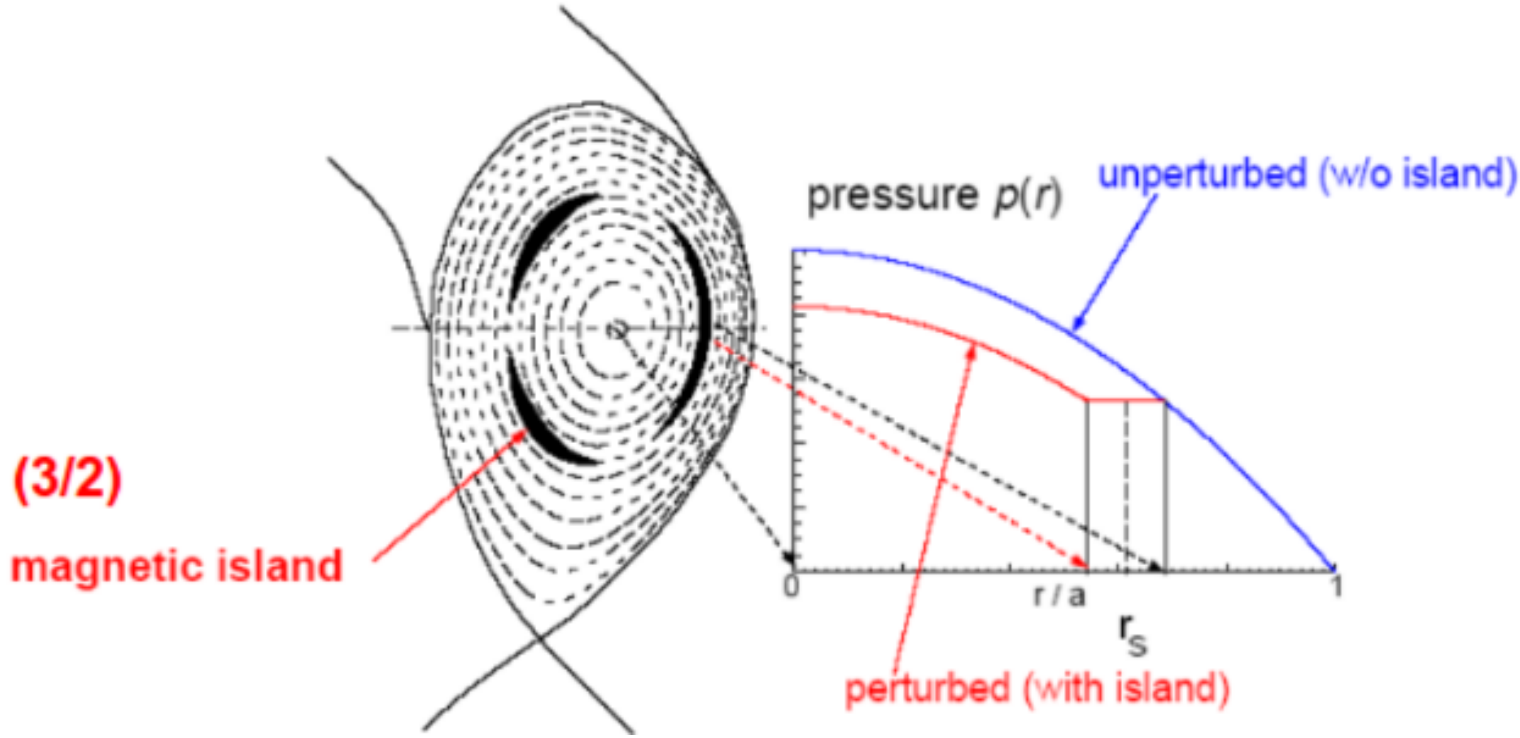
- Neo-Classical Tearing Mode (NTM) driven by bootstrap current $\propto \nabla P$
- Linearly stable $(\Delta' < 0)$, **need a seed** to flatten the pressure profile (Carrera 86)
- Control of NTM understood and efficient (Sauter 10, Widmer 19)
- Mechanism of seed need to be calrified
- **Turbulence can be a player in the NTM seeding** (Agullo 17, Ishizawa 19)
- Non-linear evolution by generalised Rutherford equation (Rutherford 73, Widmer 19)

$$\frac{0.82\mu_0 a^2}{\eta}\frac{dW}{dt} = a\Delta' + a\Delta'_{bs} + a\Delta'_{GJJ} + a\Delta'_{ctrl} + \ldots$$





ORB5 (Lagrangian PIC) solves GK Vlasov-Maxwell system of equations

Species distribution function f_s split between background $F_{0,s}$ and time dependent variation $f_s = F_{0,s} + \delta f_s$

Background control variate $F_{0,s}$ chosen as Maxwellian, δf_s found from GK Vlasov equation

$$\partial_t \delta f_s + \dot{R} \frac{\partial \delta f_s}{\delta R}\bigg|_{v_{||}} + \dot{v}_{||} \frac{\partial f_s}{\partial v_{||}} = -\dot{R}^{(1)} \cdot \frac{\partial F_{0,s}}{\partial R}\bigg|_{\varepsilon} - \dot{\varepsilon}^{(1)} \frac{\partial F_{0,s}}{\partial \varepsilon}$$

Gyro-center orbits and trajectories $\left[\dot{R}, \dot{v}_{||}\right]$ with perturbations $\left[\dot{R}^{(1)}, \dot{v}_{||}{}^{1}\right]$

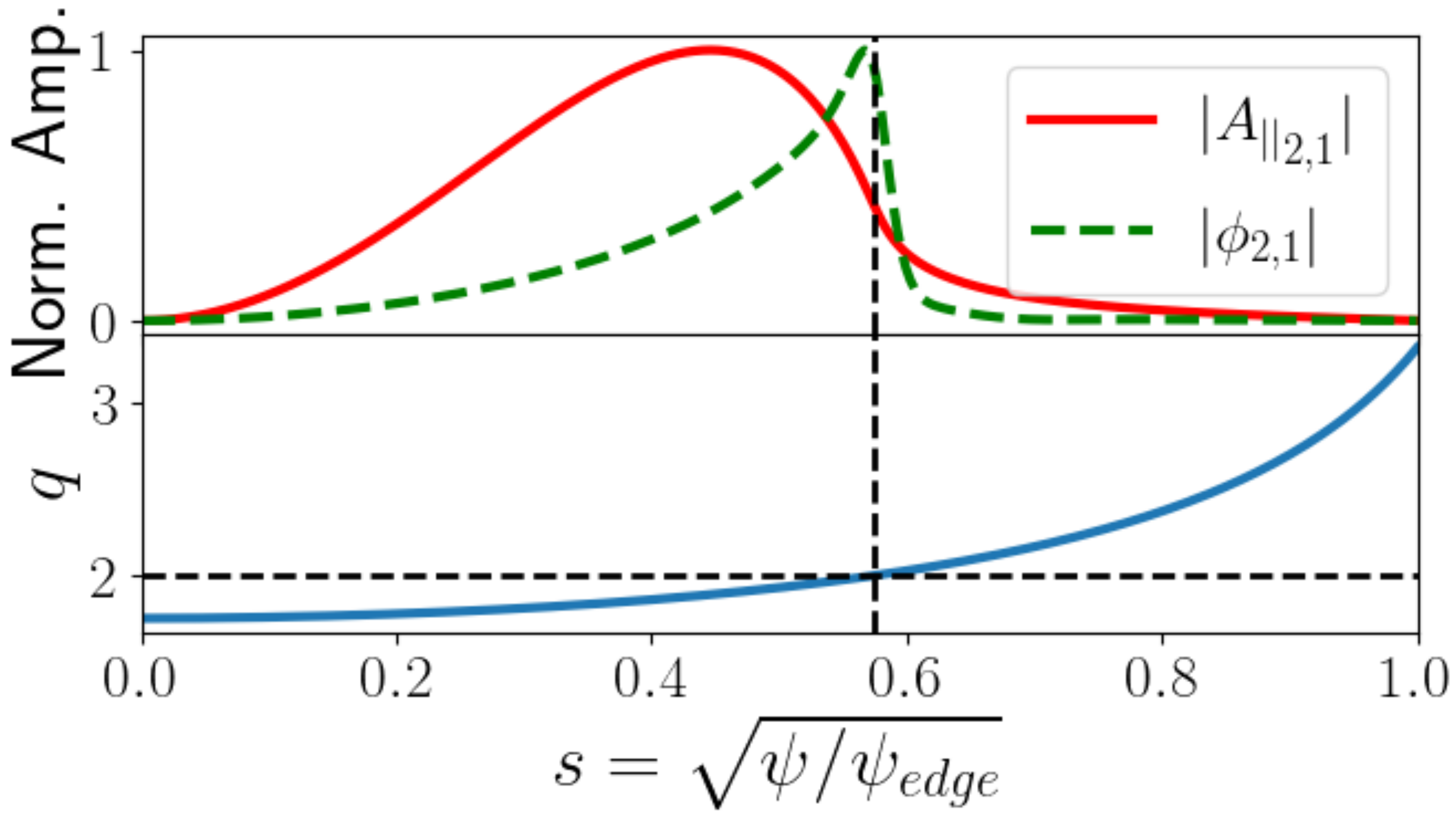
Total energy $\varepsilon = \varepsilon_{||} + \varepsilon_{\perp} = \frac{1}{2} v_{||}^2 + \mu B$ with $\mu = \frac{v_{\perp}^2}{2B}$

Initial unstable current profile (Wesson 2011)

$$j = j_0 \left(1 - \left(\frac{r}{a}\right)^2\right)^{\zeta} \qquad q = q_a \frac{r^2/a^2}{1 - (1 - r^2/a^2)^{\zeta+1}} \qquad \text{with} \quad \zeta = 1$$

Shifted Maxwellian for the electrons produces ***J*** consistent with ***q***

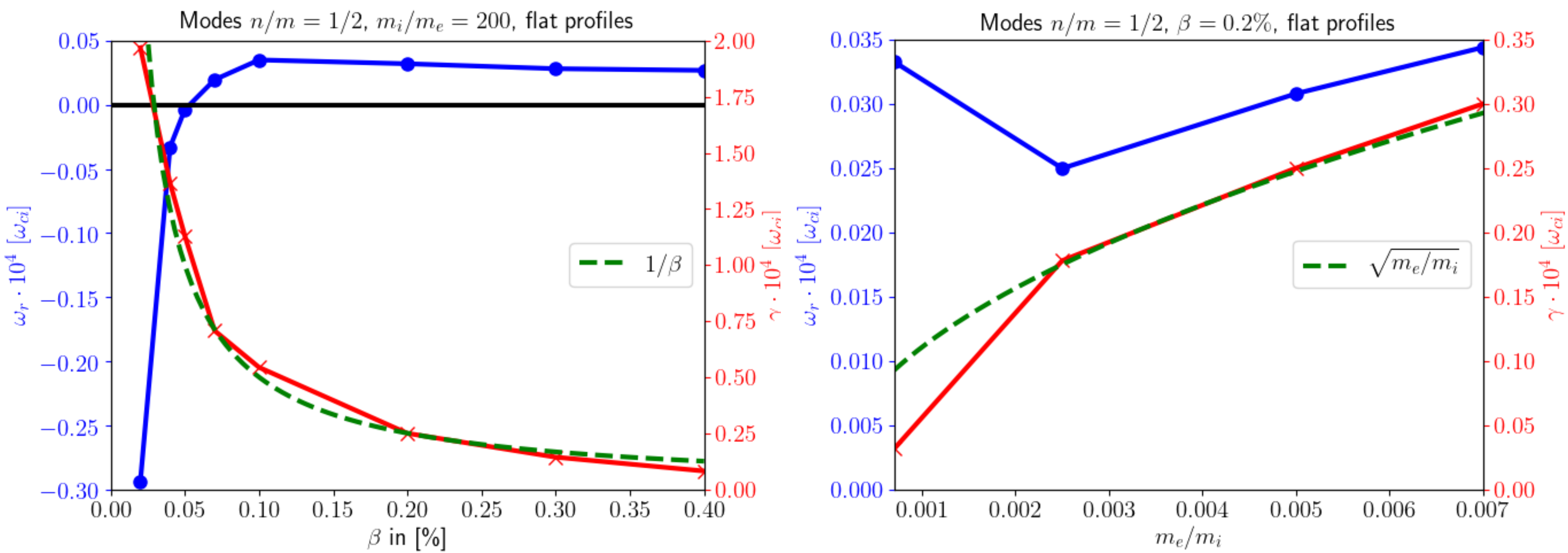
- Mass ration m_i/m_e=200
- Large aspect ratio R_0/a=10
- $\rho^* = \rho/a = 1/100$



- Kinetic estimation of the growth rate (Rogers 2007)
- $\gamma_{cl}/\gamma_{ci} = \Delta' \rho_{se} k_\theta \rho_{se} \left(\frac{m_e}{m_i}\right)^{1/2} \frac{1}{T_e^{1/2}} (T_e + T_i)^{1/2} \frac{1}{\beta_e}$ Validity: $m_e/m_i < \beta$

Linear simulations with flat profiles in good agreement

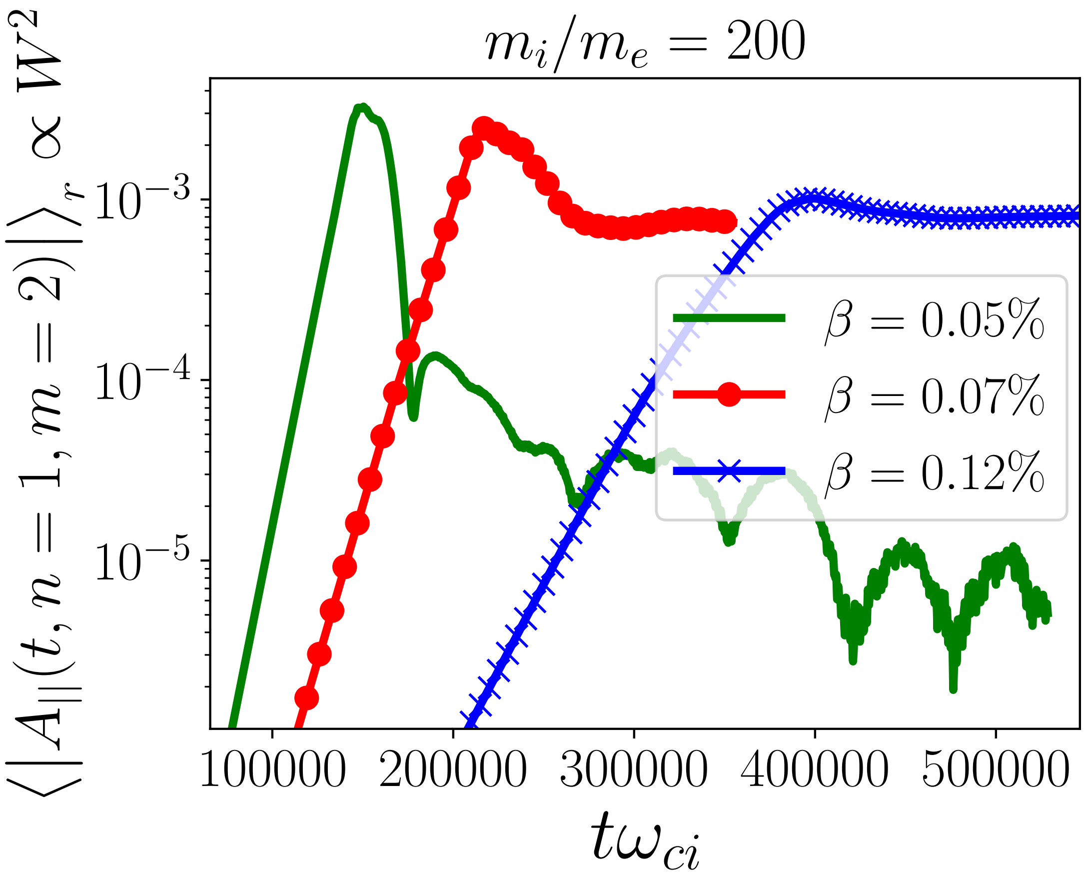
- β-scan, fixed T_e=T_i and m_e/m_i = 0.005
- Mass scan, fixed T_e=T_i and β =0.2%

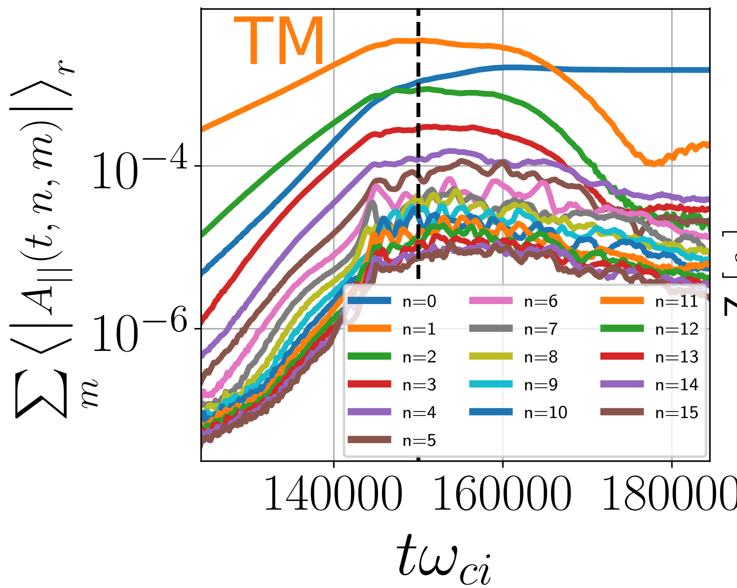


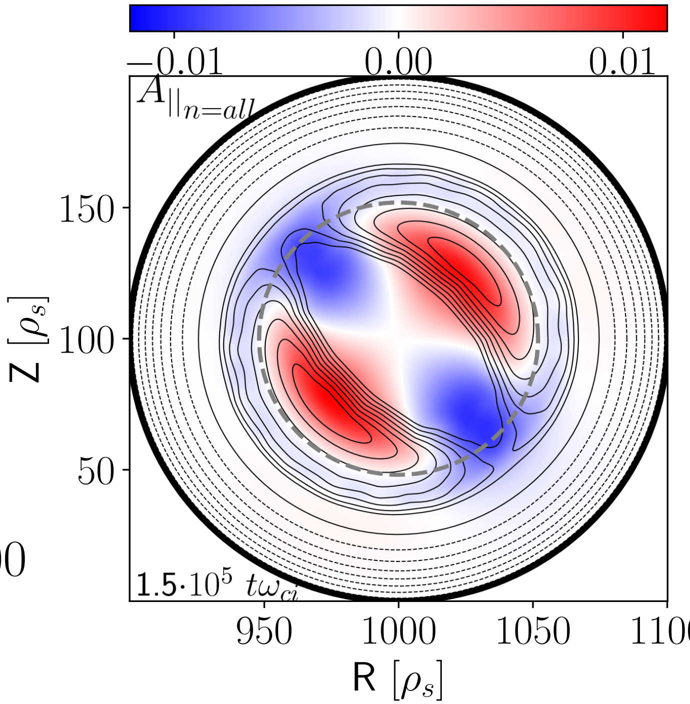
1) Introduction
2) Tearing mode initialisation and validation
3) Strongly Driven Tearing Modes:
    a) Current density redistribution
    b) Kelvin-Helmholtz instability
4) Tearing mode and ITG
5) Conclusions

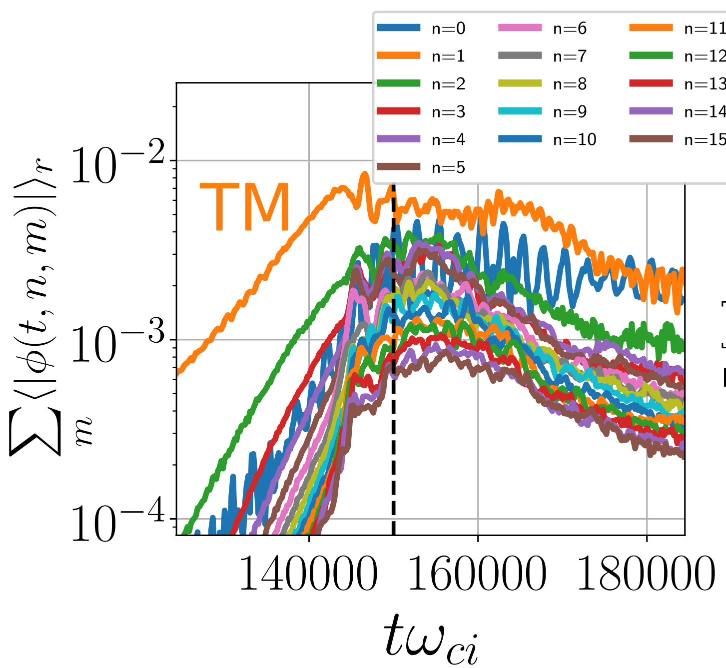
Flat Density and Temperature Profiles

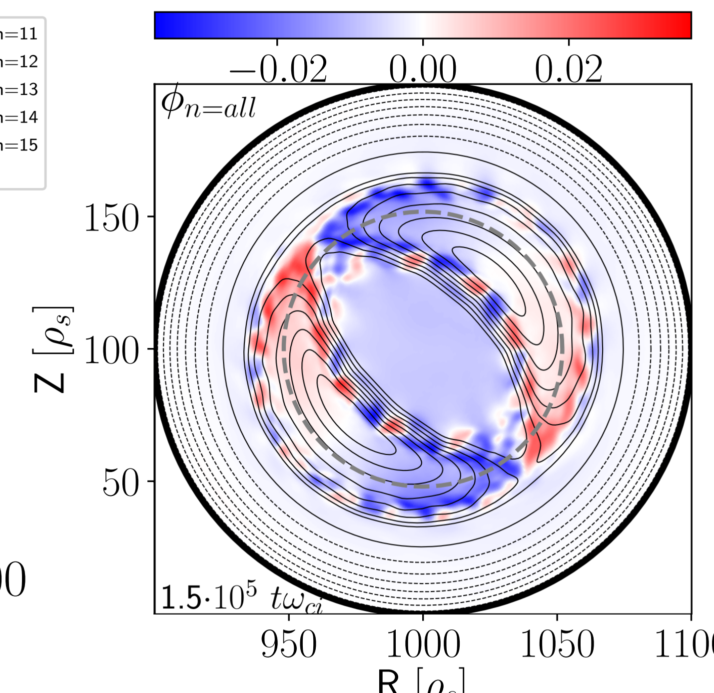
- Strongly driven tearing mode has a strong size reduction
- Turbulence develops at the separatix
- Zonal magnetic fields grow at twice the TM growth



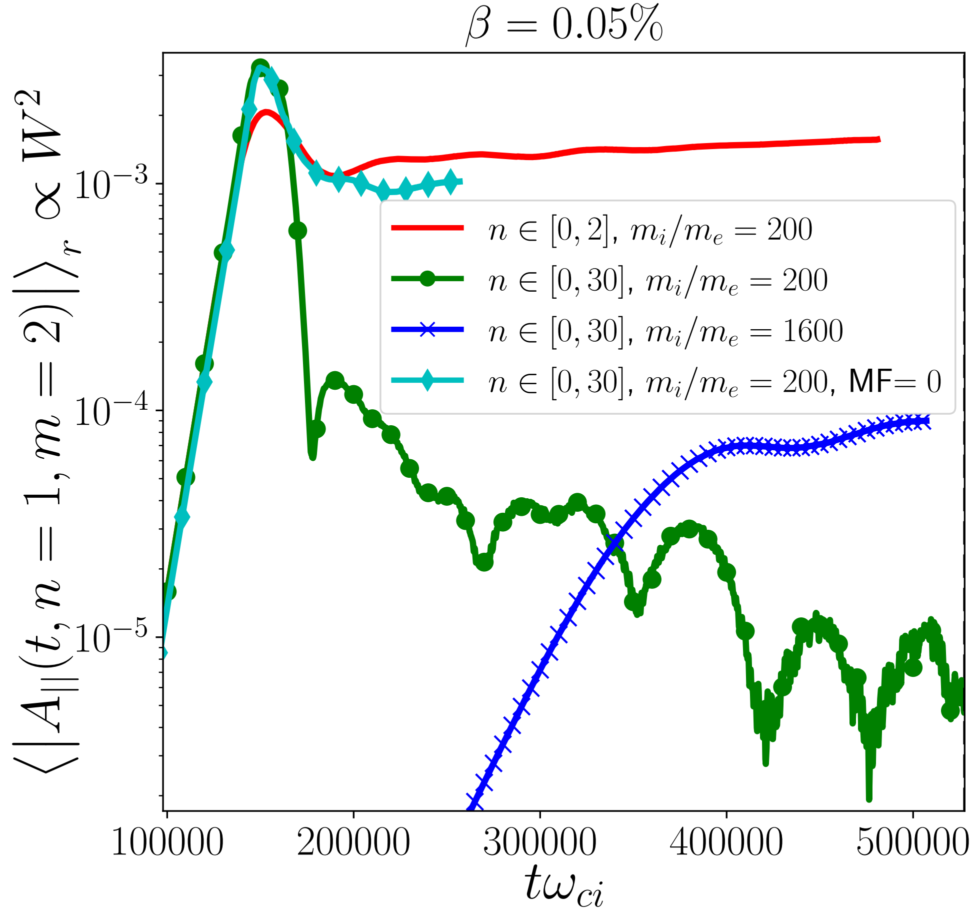


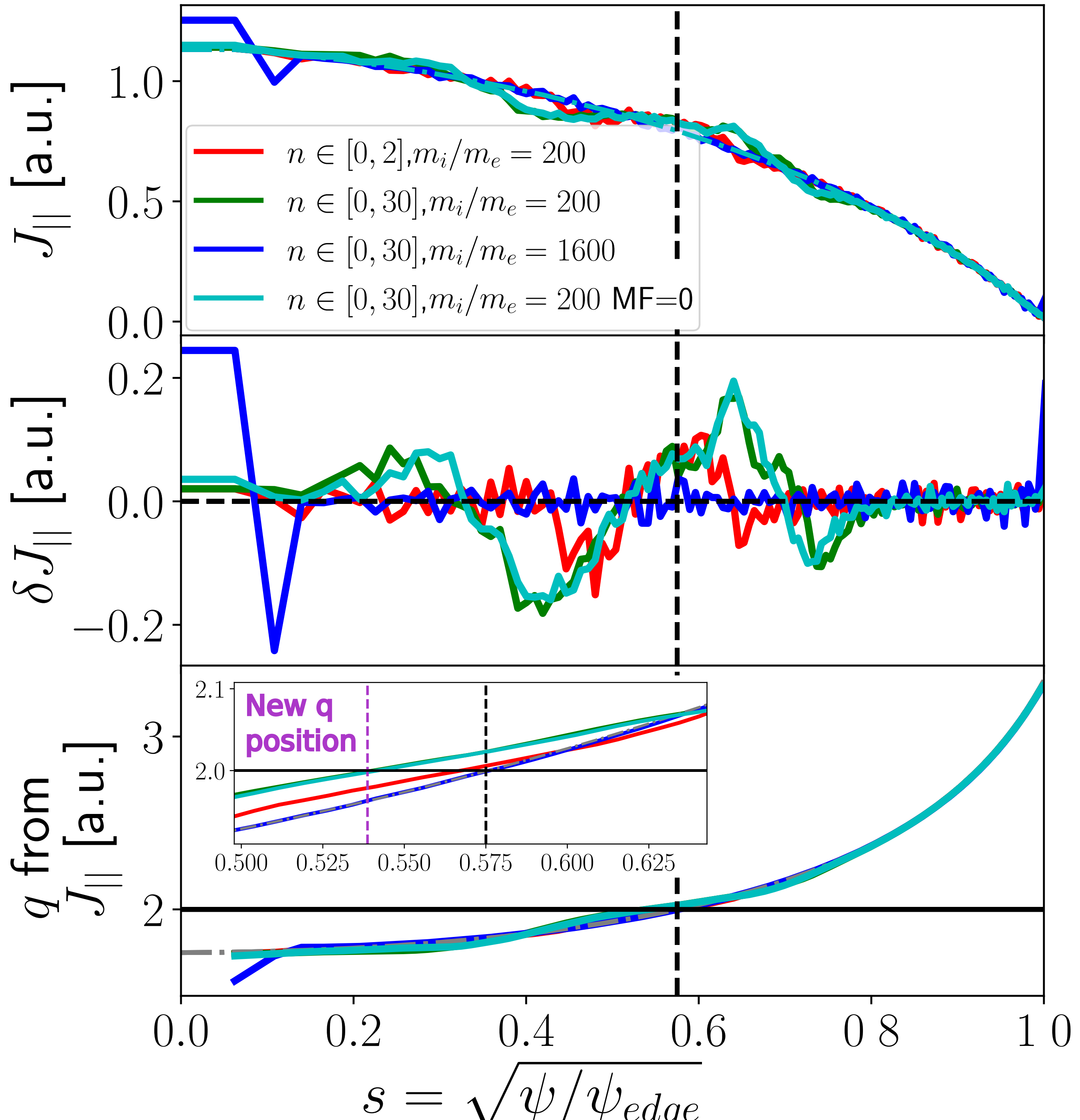




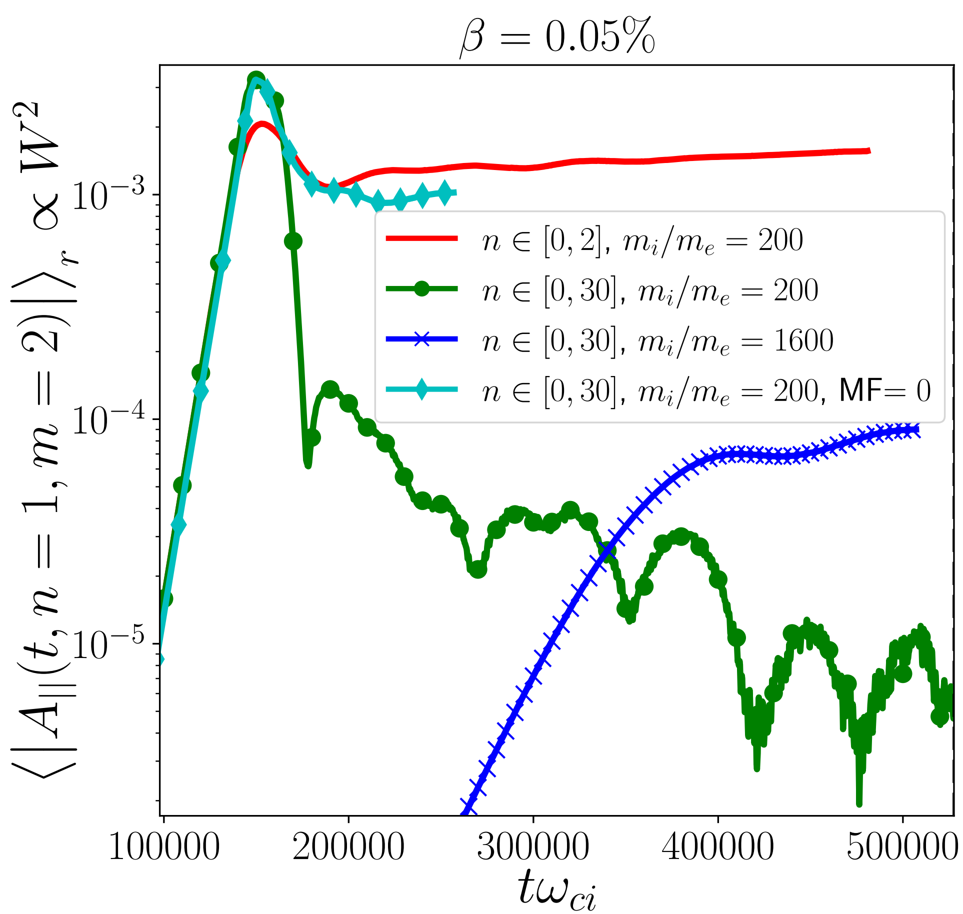


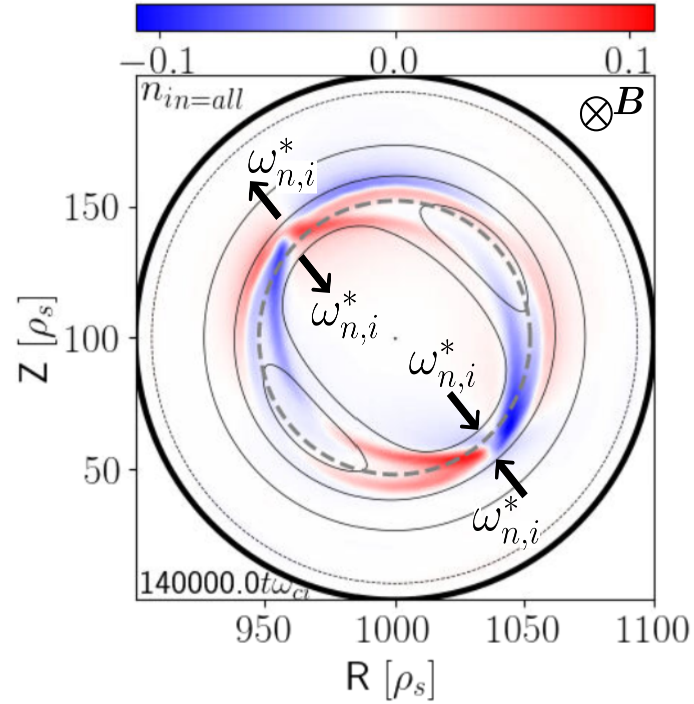
- Large islands induce strong zonal magnetic fields that impact the island size through modification of background current density $J_{||}$ and safety factor q

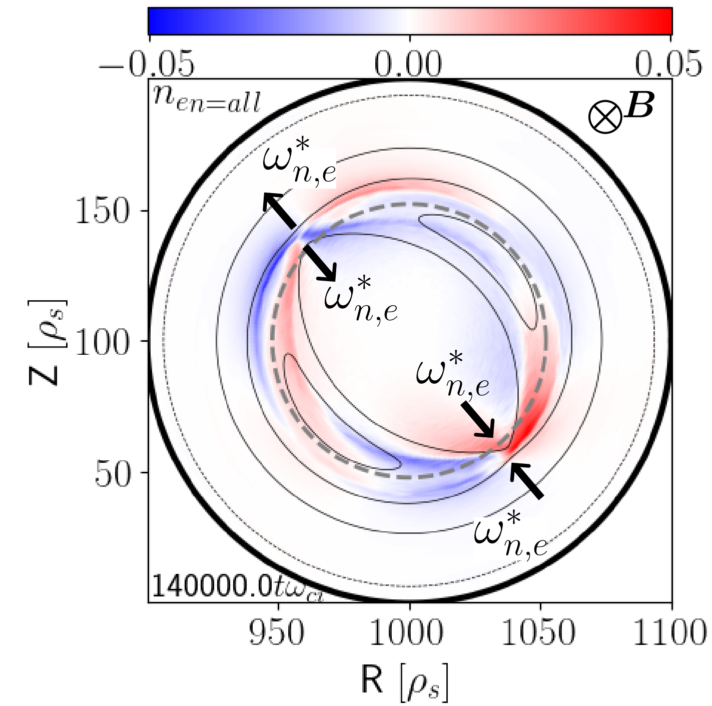




- Island size initial reduction not related to turbulence
- Turbulence enhances the island healing.
- Trapped electrons important!



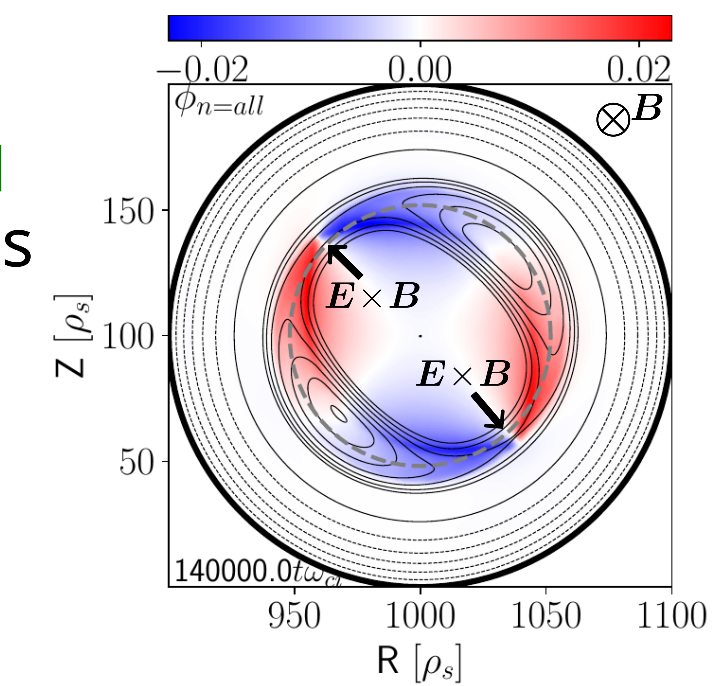




- Typical localised density and ϕ [1,2]
- Inflows at X-points

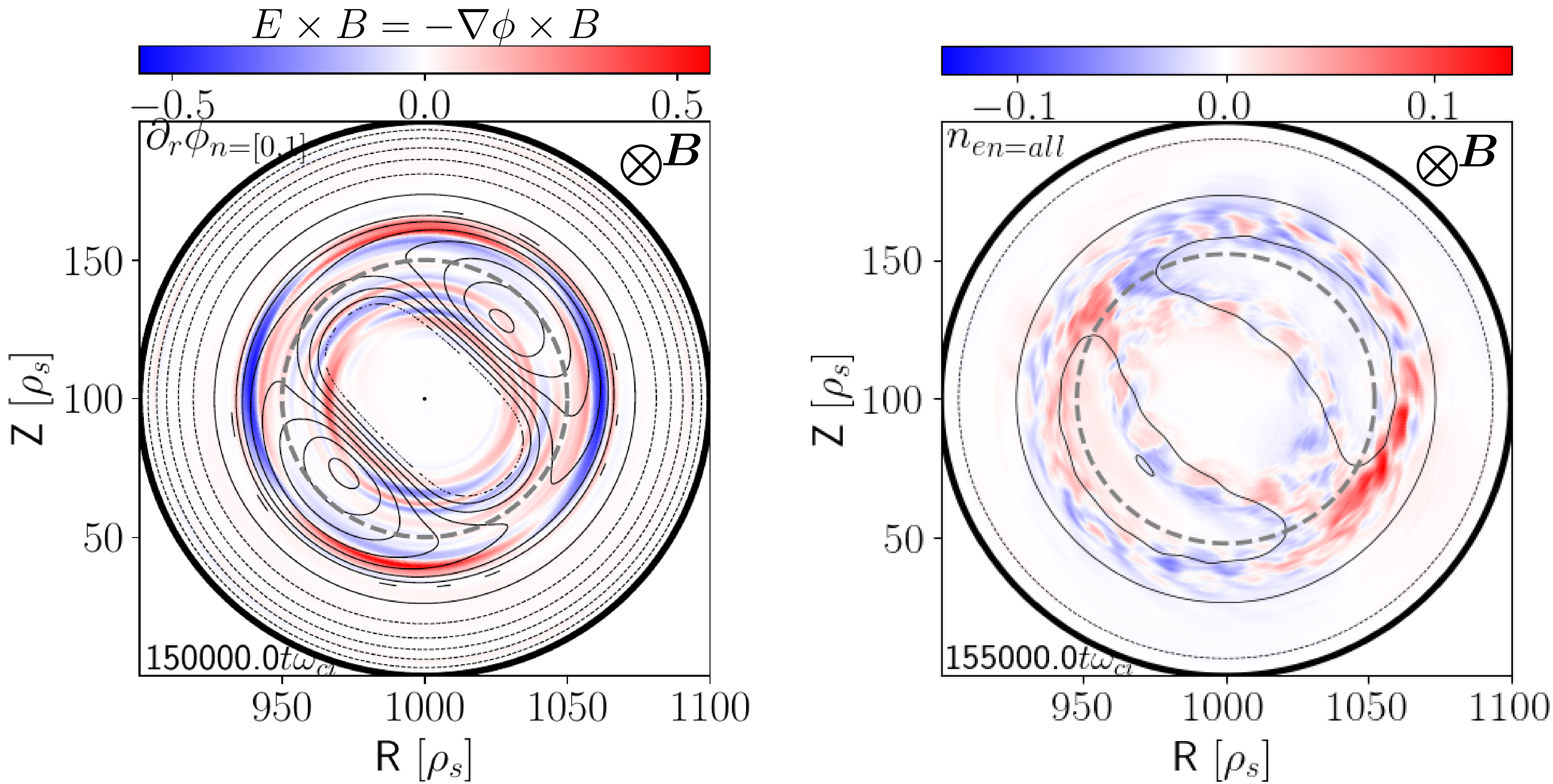
$$\omega^*_{n,s} = -\frac{\nabla n_s \times B}{q_s}$$

$$E \times B = -\nabla \phi \times B$$



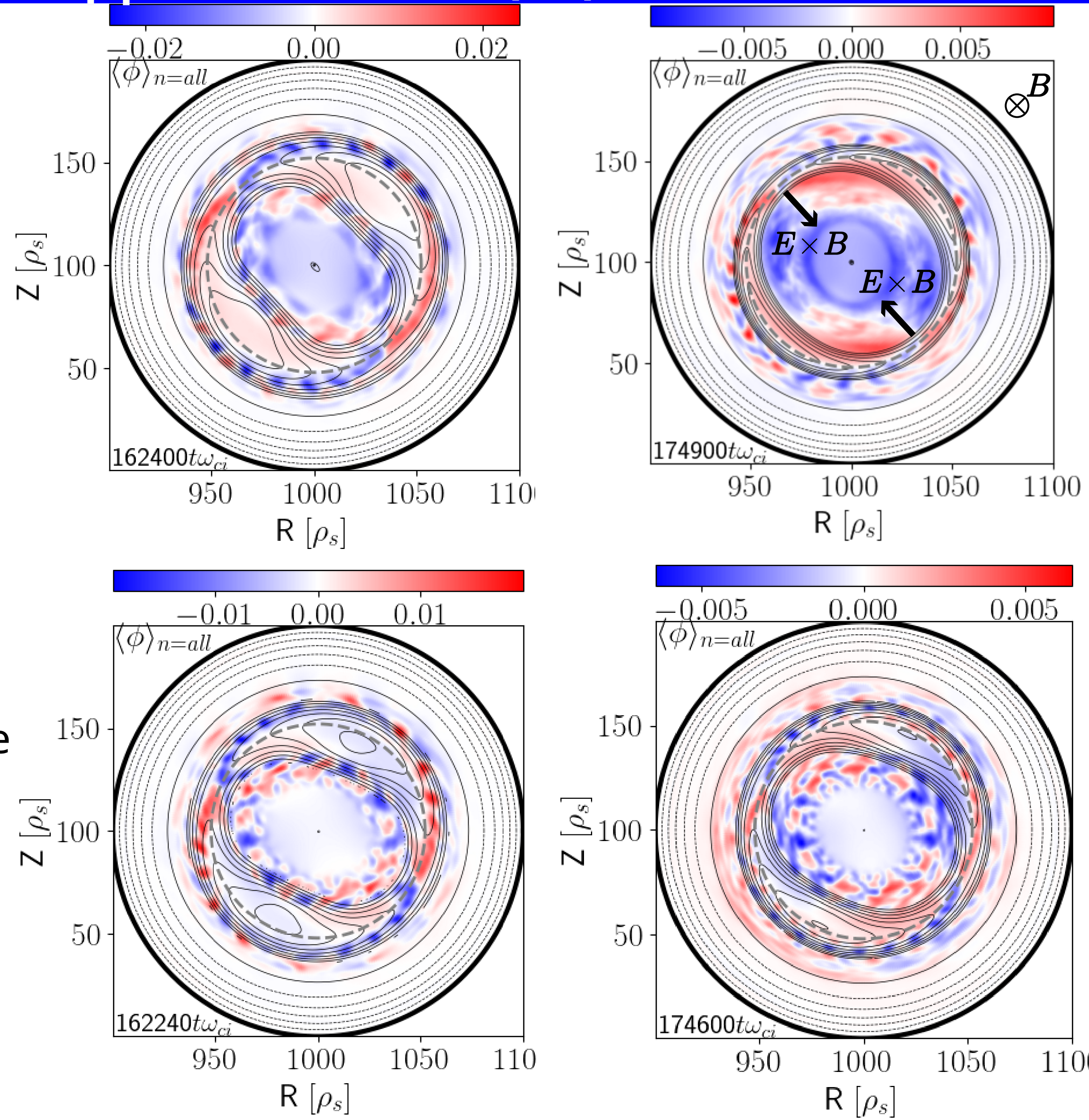
[1] Biskamp 00
[2] Kleva PoP 95

- Large islands induce strong quadrupolar sheared flows
- Localised density and ϕ unstable to KHI [3] Granier PoP 24

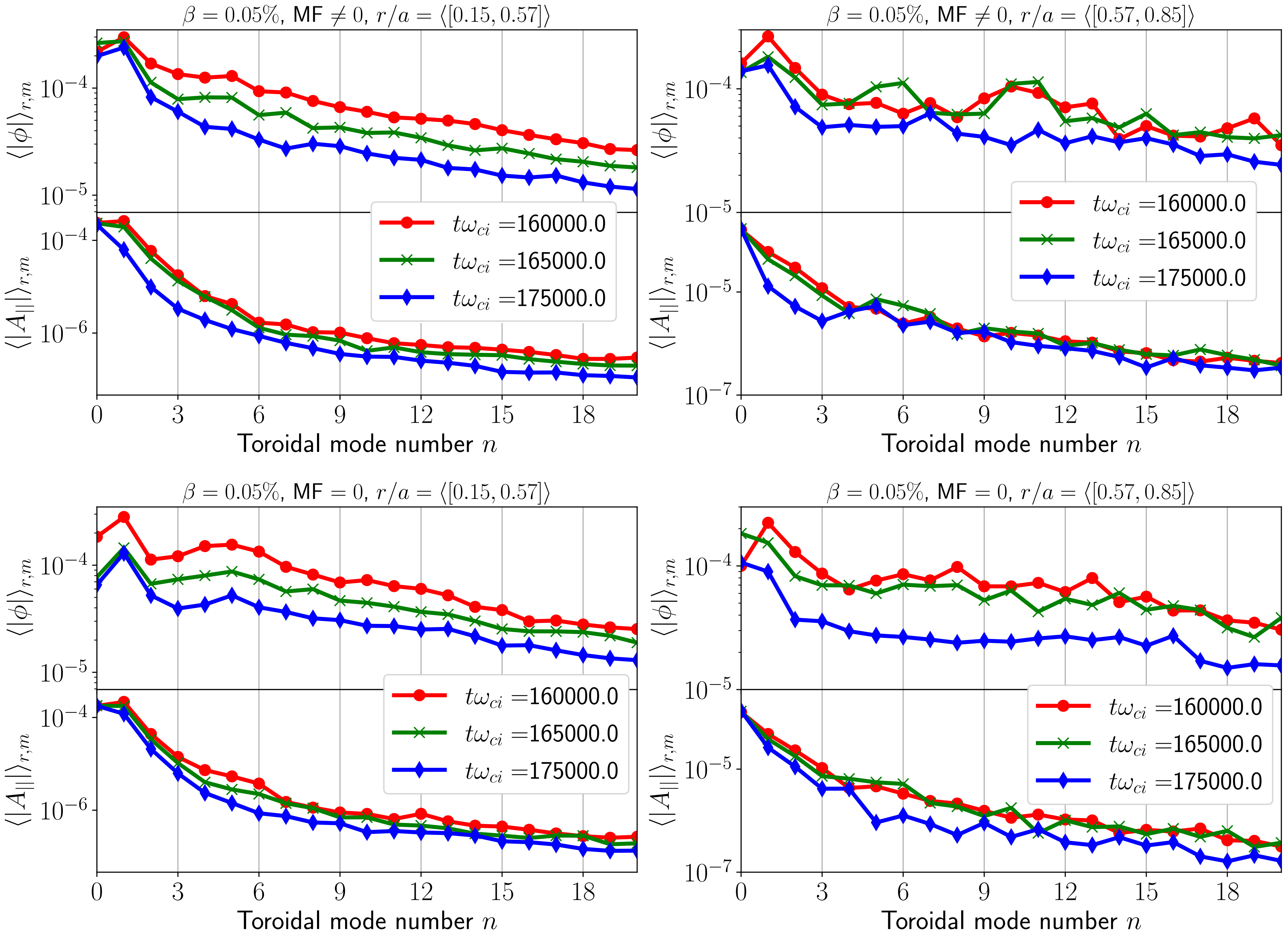


Impacts of Trapped Electrons (TE) I

- KHI turbulence redistributes the flows
- Inner region :
  - Turublence changed from m~10 to m~2 with trapped electrons → Strong outflows.
  - Turbulence with m~10 remains without trapped electrons
- Outer region :
  - Unclear but KHI induced turbulence seems to survive

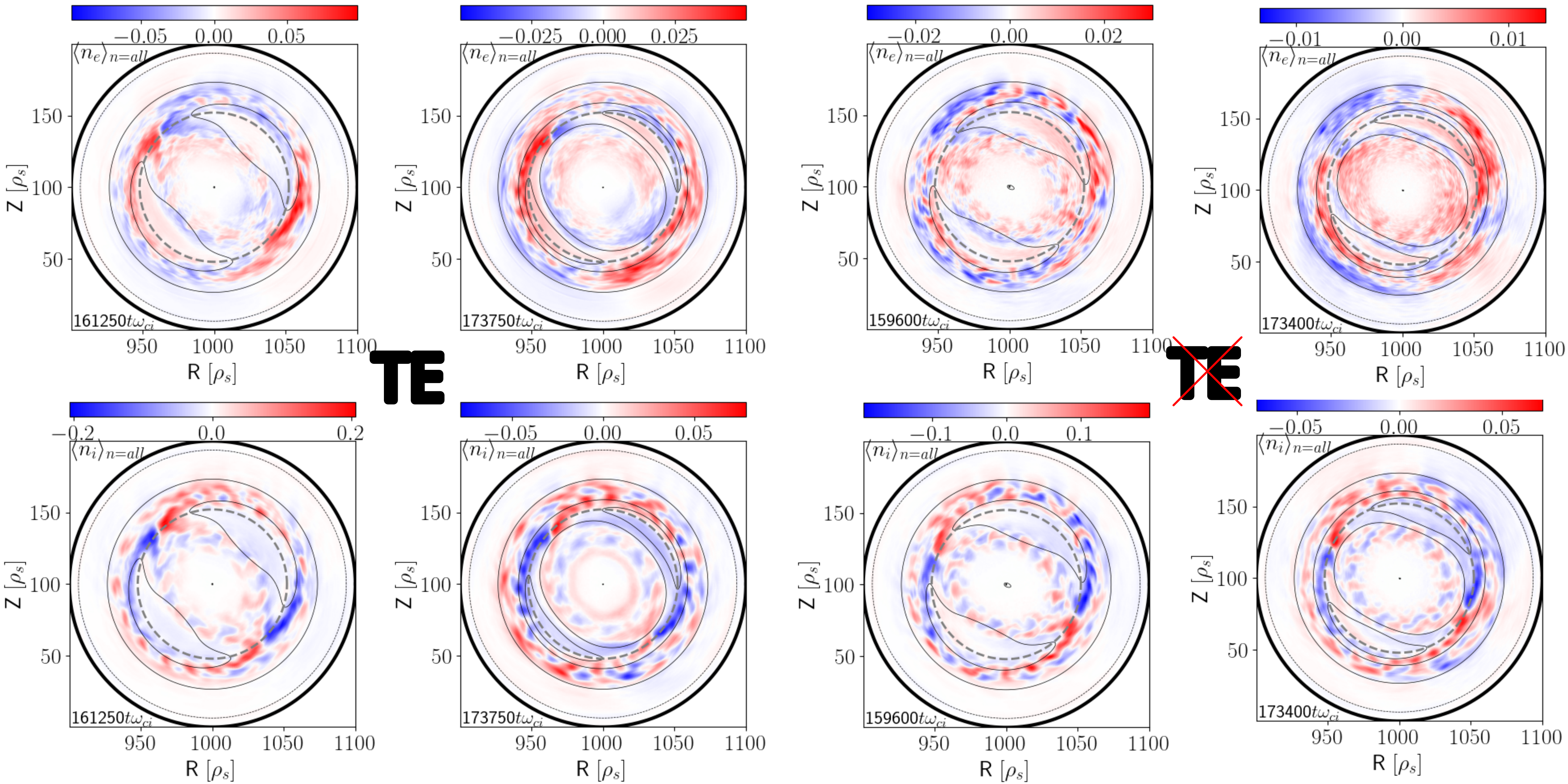


- With TE
  - Inner region :
    n=1 stagnates
  - Outer region:
    Peaks for n=10 and 6
- Witouth TE
  - Inner region :
    n=1 decreases
    and n=5 remains
  - Outer region :
    n=0,1 dominate
- Consistent with
  the $\boldsymbol{E}\times\boldsymbol{B}$ flows picture



Impacts of Trapped Electrons (TE) III

Diamagnetic flows more difficult to interpret but electrons flows seem more affected



Strong Island Healing Conclusion

I. Current density redistribution:

i. Strongly driven tearing mode produces large islands
ii. Growth of important zonal fields $\boldsymbol{A}_{||}(m = 0, n = 0)$ independently of turbulence
iii. Current density redistribution generates perturbed currents at the island separatrix
iv. Flattening of the radial current density profile within the island
v. Island drive is diminished and its size reduced

II. Island-induced flows:

i. Intense quadrupolar flows at island separatrix
ii. Localised quadrupolar ϕ and density around the X-points
iii. Fields become KH unstable which then modifies the flows pattern
iv. Trapped electrons driven instability further boosts the flows
v. Flows responsible for the strong reduction of the island size

III. Trapped electrons seem essential for the island healing process

This scenario can be of interest for strongly driven magnetic reconnection like sawtooth events