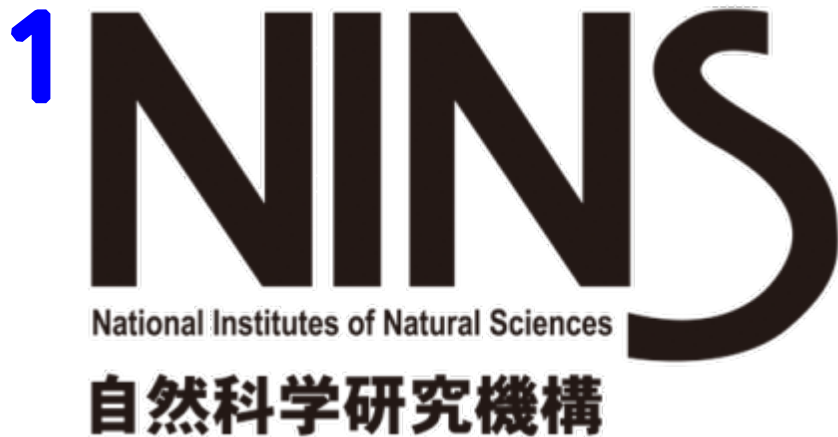


Island-Turbulence interactions and Role of Zonal Flows

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FÜR PLASMAPHYSIK

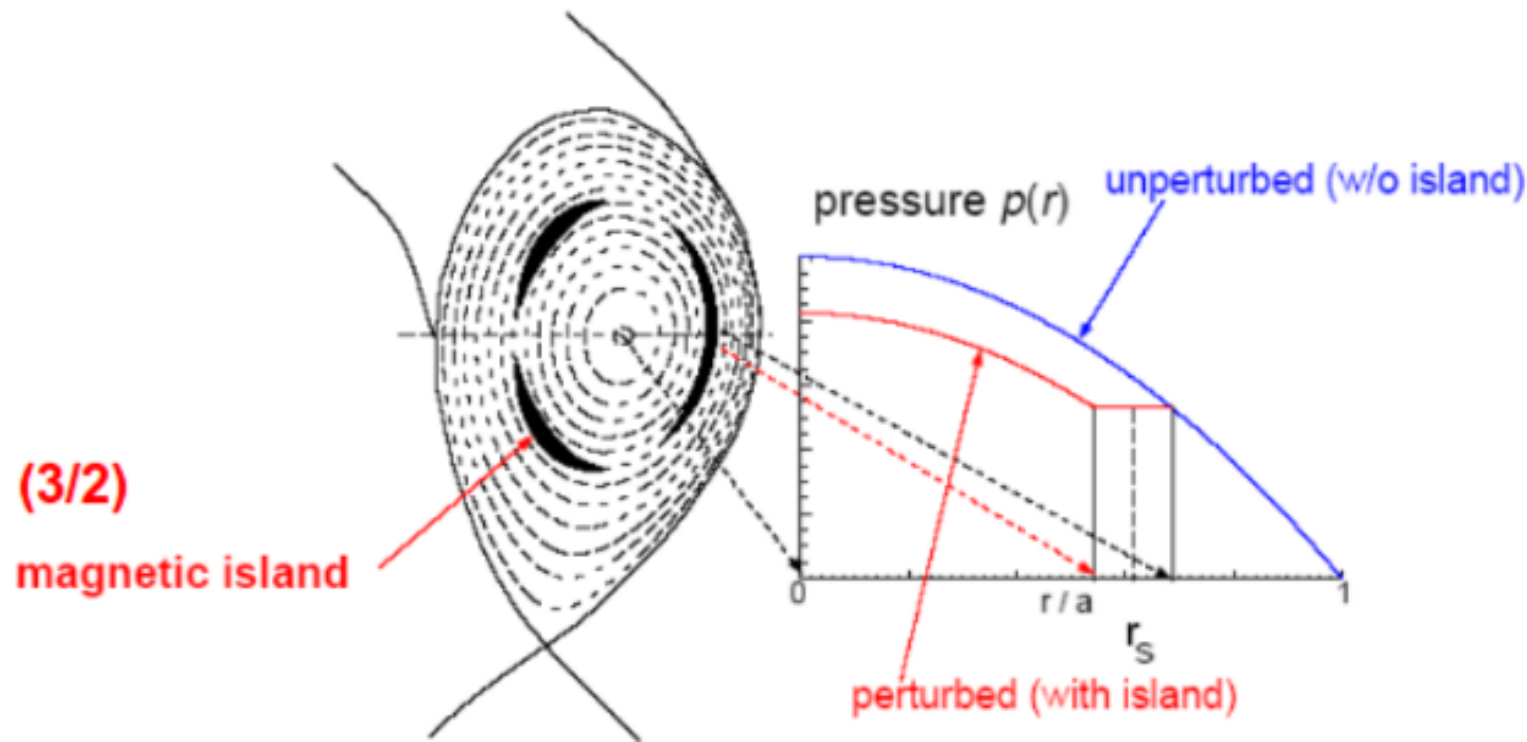
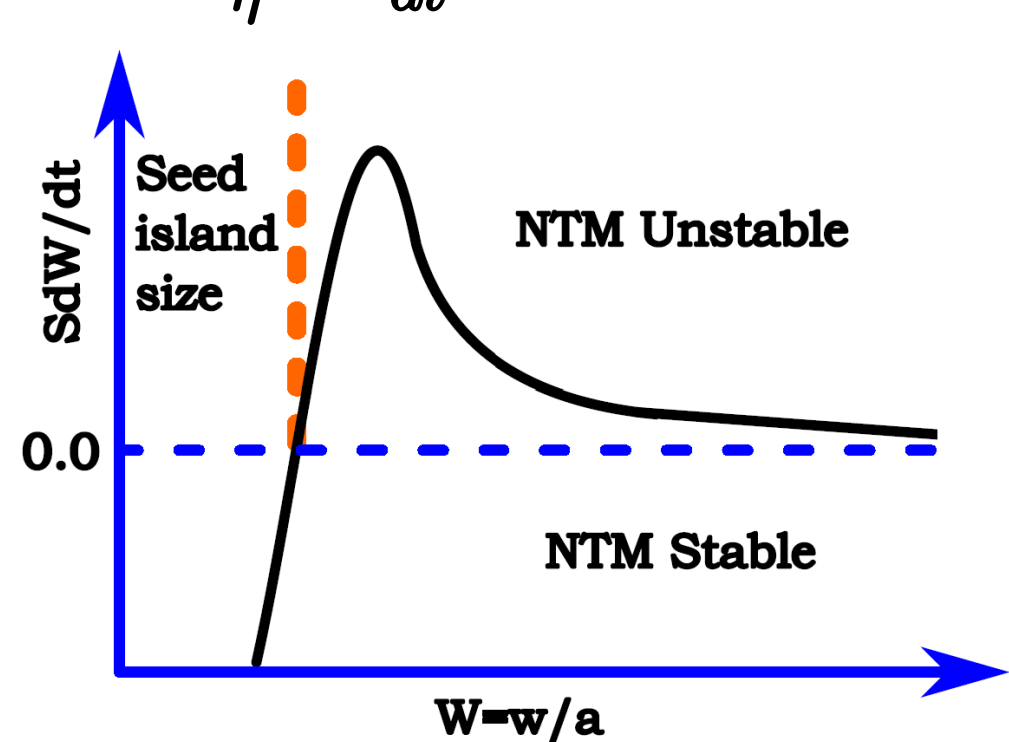


- 1) Introduction
- 2) Tearing mode initialisation and validation
- 3) Strongly Driven Tearing Modes:
 - a) Current density redistribution
 - b) Kelvin-Helmholtz instability
- 4) Tearing mode and ITG
- 5) Conclusions

Introduction: NTM Problem

- 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 clarified
- **Turbulence can be a player in the NTM seeding** (Agullo 17, Ishizawa 19)
- Non-linear evolution by generalised Rutherford equation (Rutherford 73, Widmer 19)

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



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Tearing Mode Initialisation in ORB5

Initial unstable current profile (Wesson 2011)

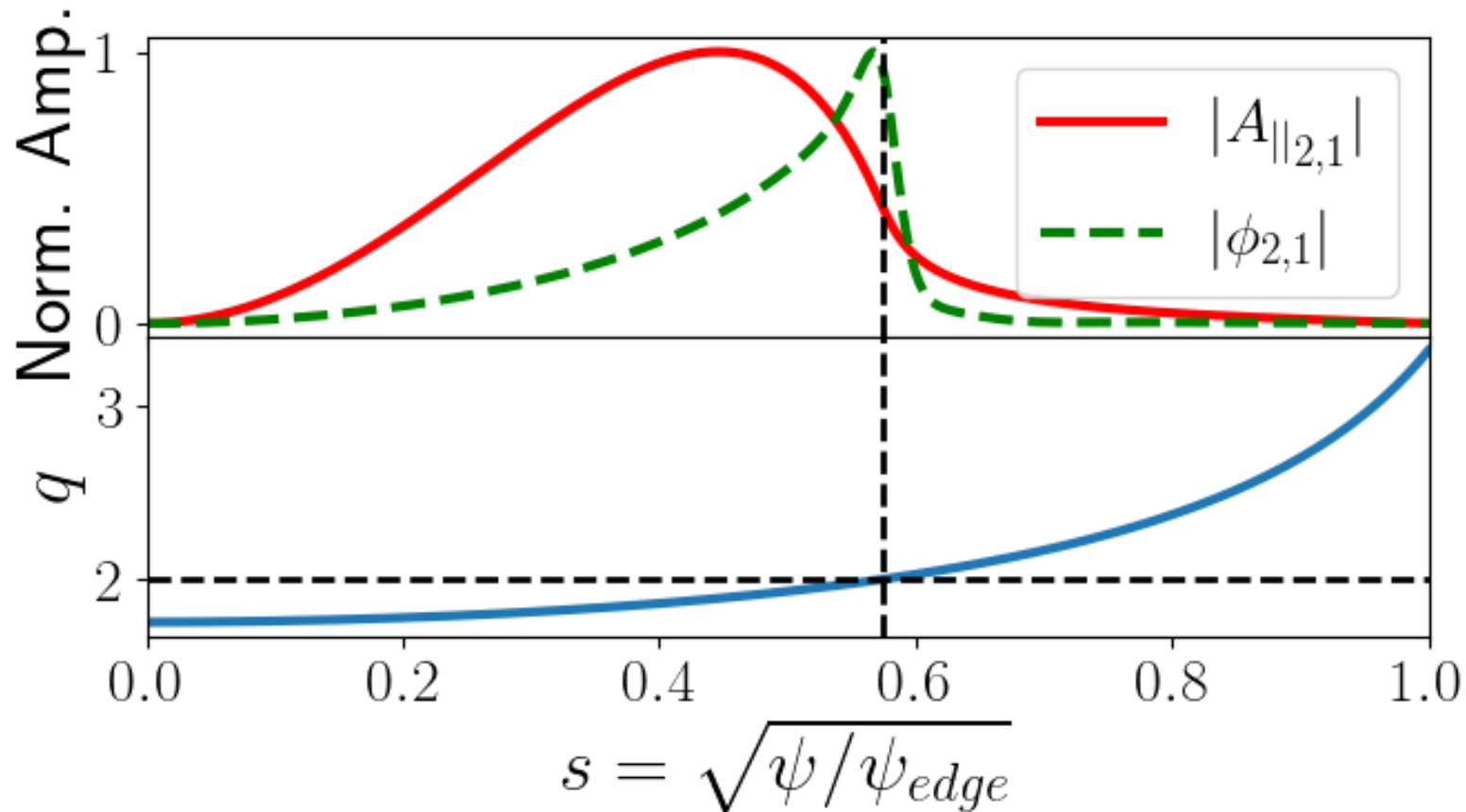
$$j = j_0 \left(1 - \left(\frac{r}{a} \right)^2 \right)^\zeta \quad q = q_a \frac{r^2/a^2}{1 - (1 - r^2/a^2)^{\zeta+1}} \quad \text{with } \zeta = 1$$

Shifted Maxwellian for the electrons produces \mathbf{J} consistent with \mathbf{q}

• Mass ratio $m_i/m_e=200$

• Large aspect ratio $R_0/a=10$

• $\rho^* = \rho/a = 1/100$



Tearing Mode Validation with ORB5

- 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: $m_e/m_i < \beta$

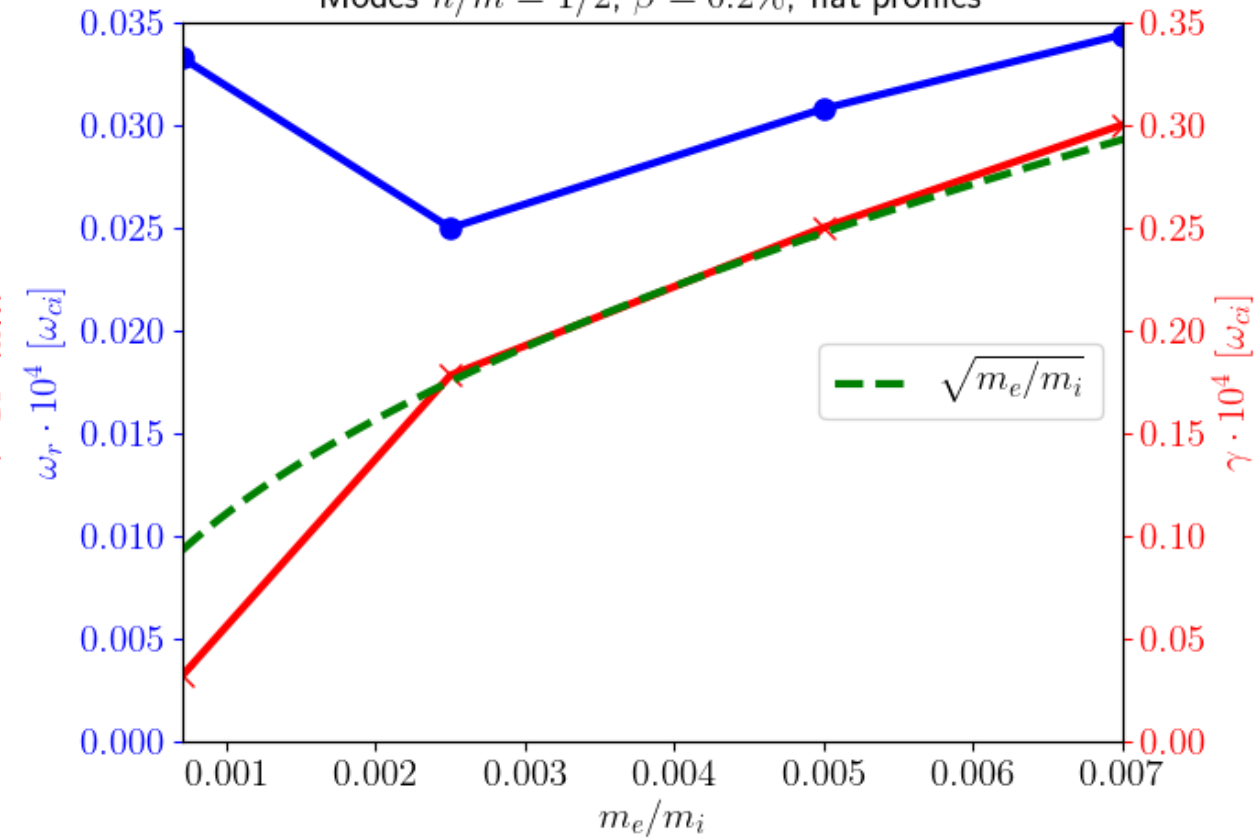
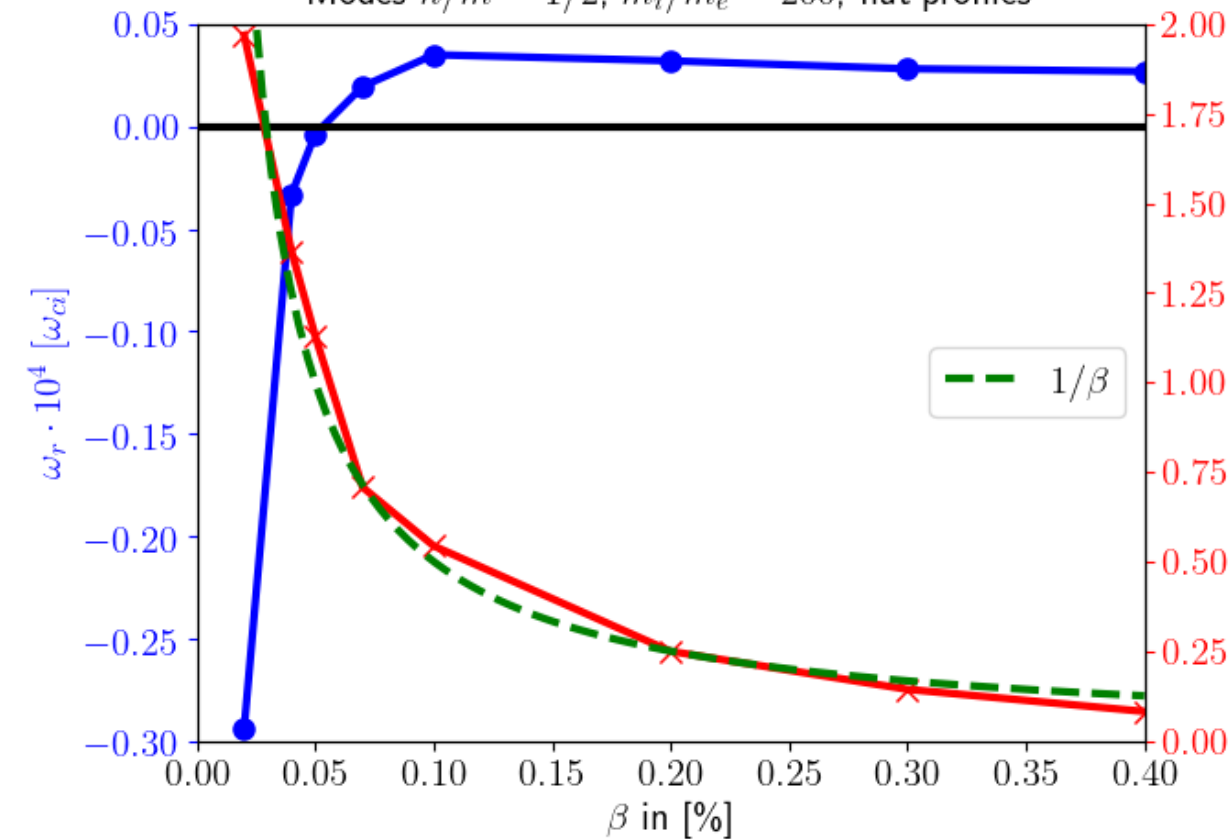
Linear simulations with flat profiles in good agreement

- β -scan, fixed $T_e=T_i$ and $m_e/m_i = 0.005$

- Mass scan, fixed $T_e=T_i$ and $\beta = 0.2\%$

Modes $n/m = 1/2$, $m_i/m_e = 200$, flat profiles

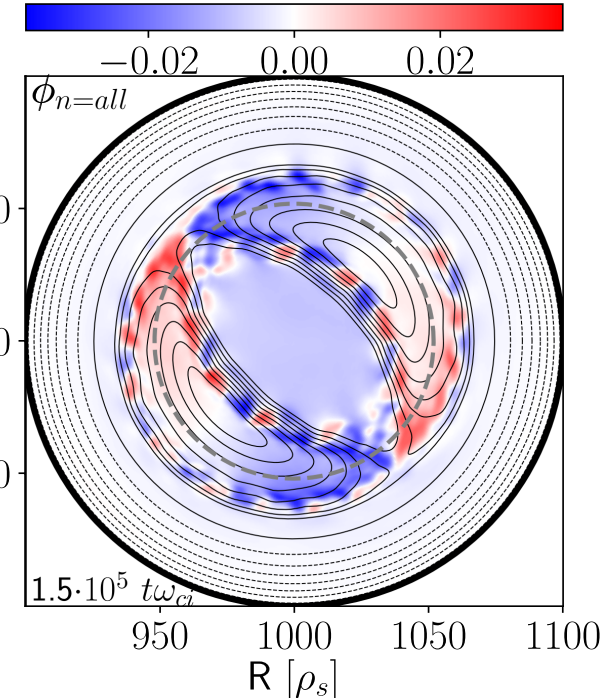
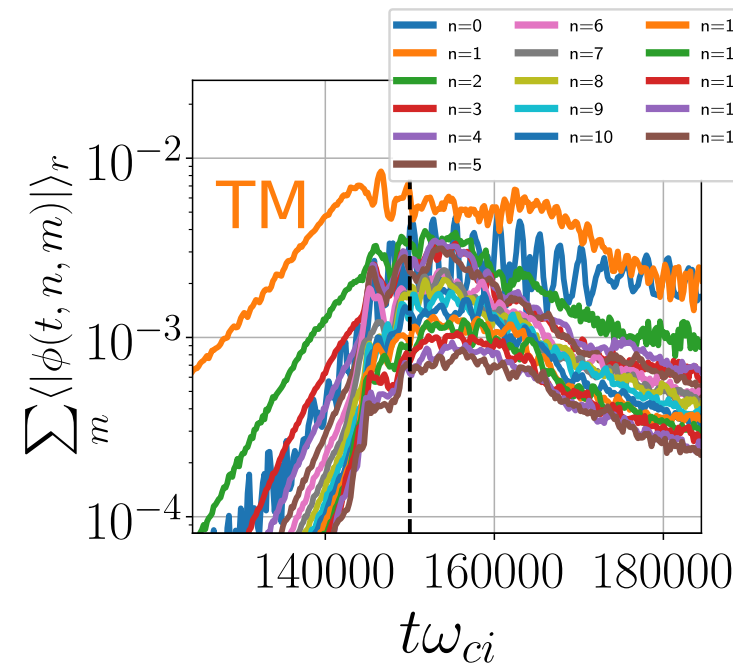
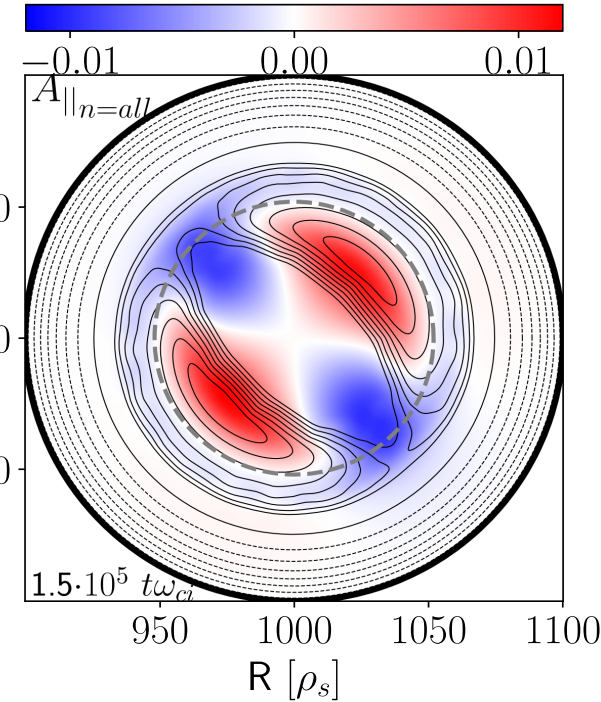
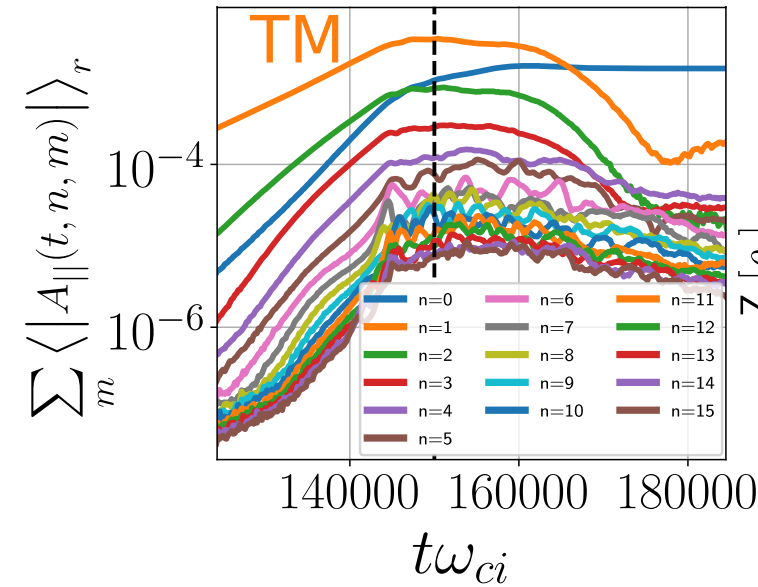
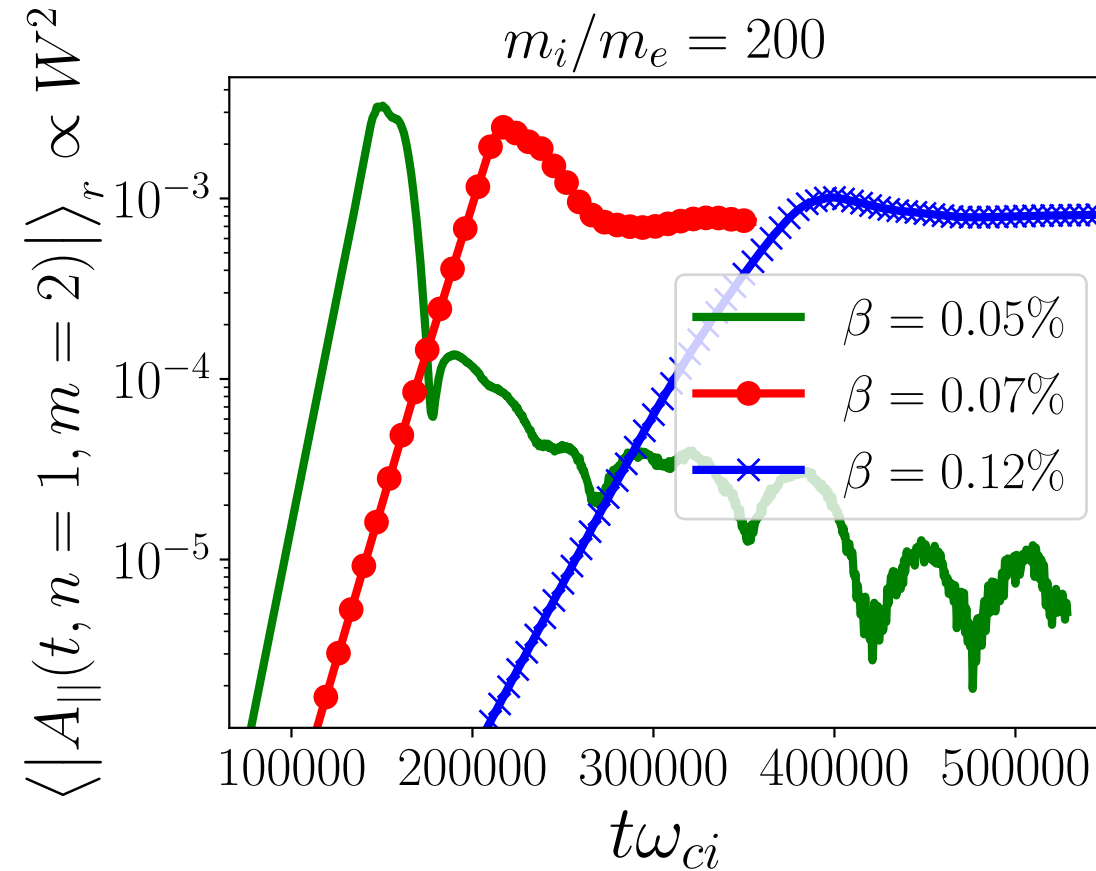
Modes $n/m = 1/2$, $\beta = 0.2\%$, flat profiles



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Flat Density and Temperature Profiles

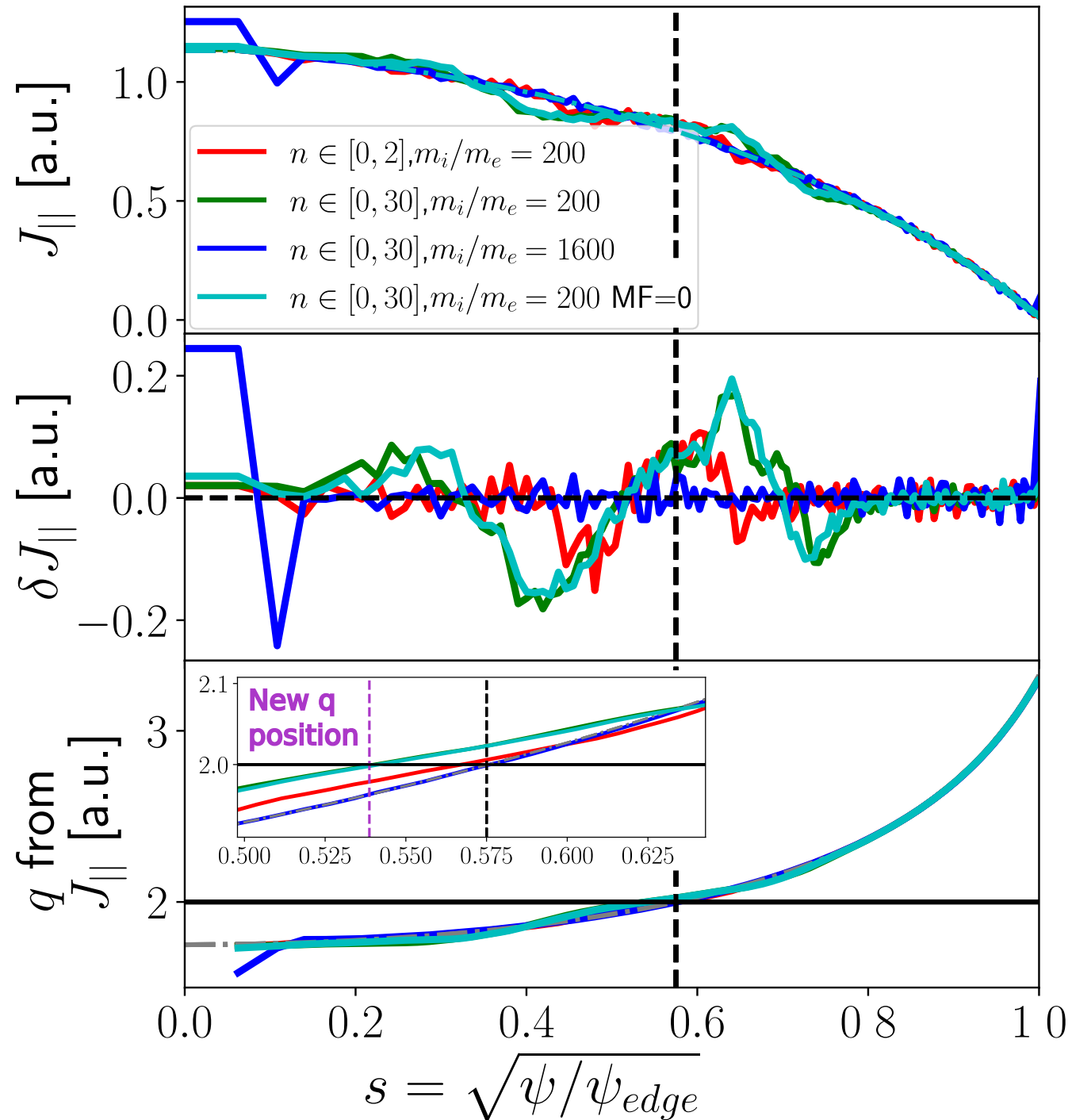
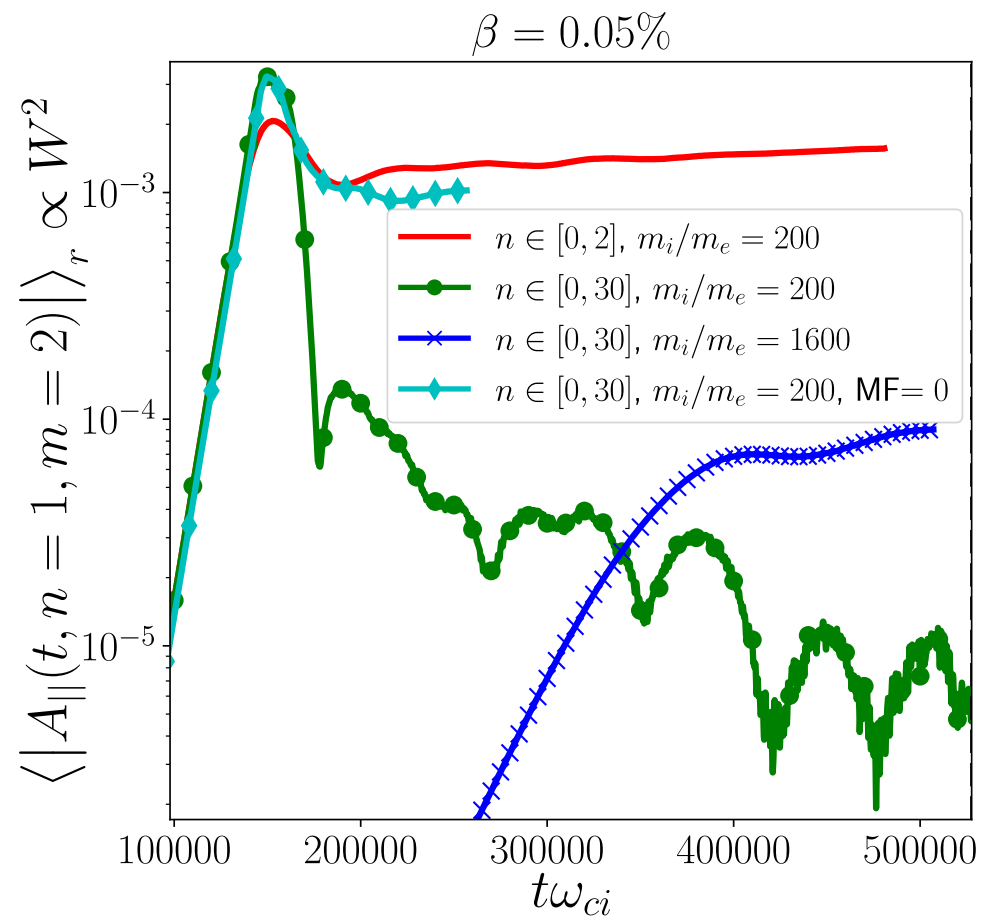
- Strongly driven tearing mode has a strong size reduction
- Turbulence develops at the separatrix
- Zonal magnetic fields grow at twice the TM growth



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Island Initial Decay: Current Redistribution

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

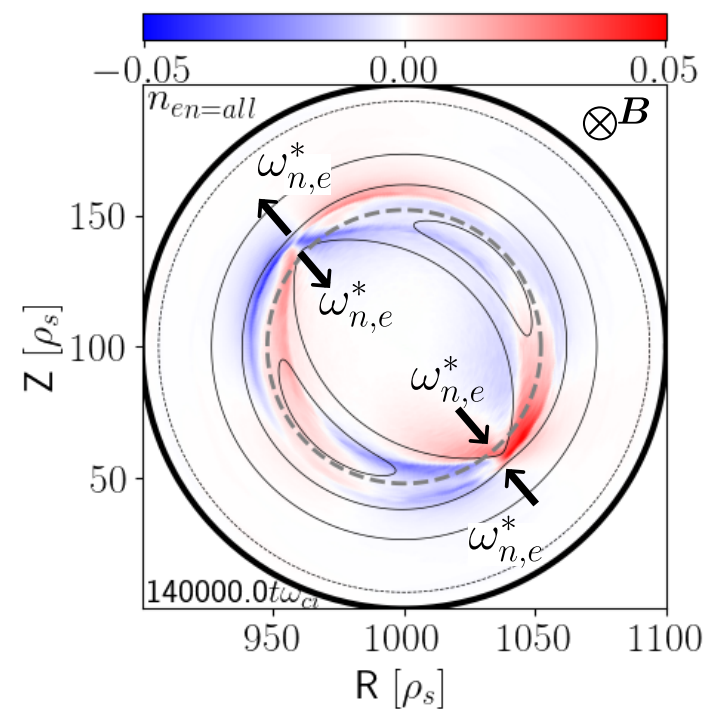
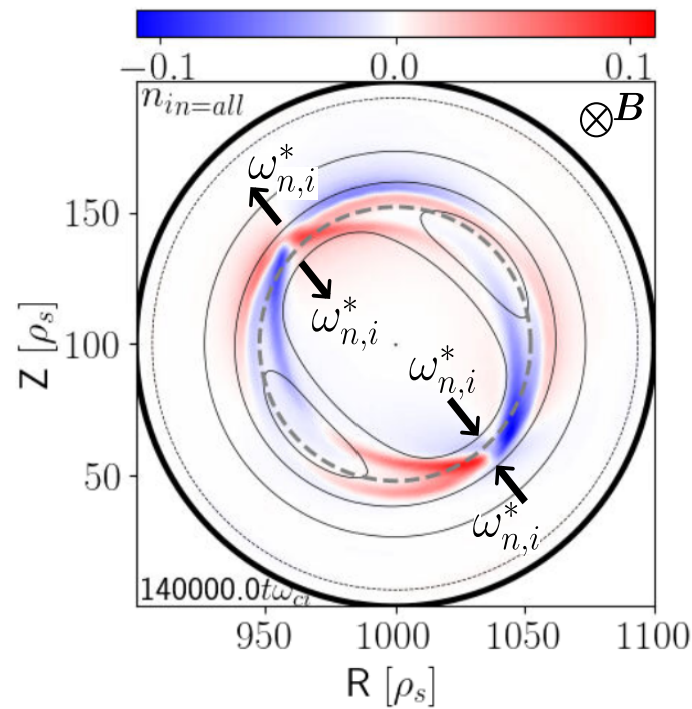
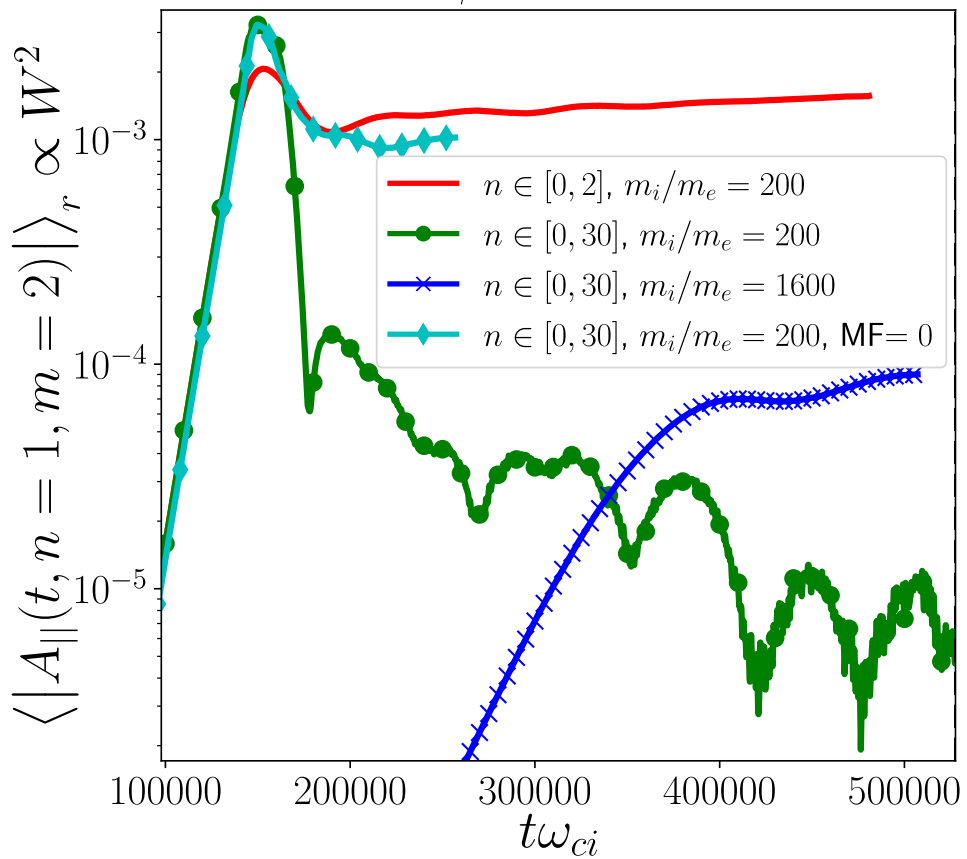


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Strong Island Healing Case $\beta = 0.05\%$

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

$\beta = 0.05\%$

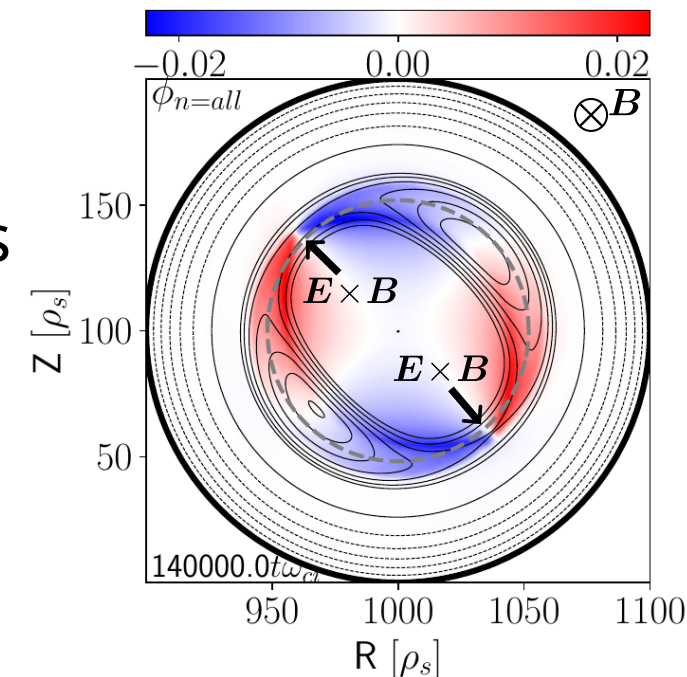


- Typical localised density and ϕ [1,2]
- Inflows at X-points

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

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

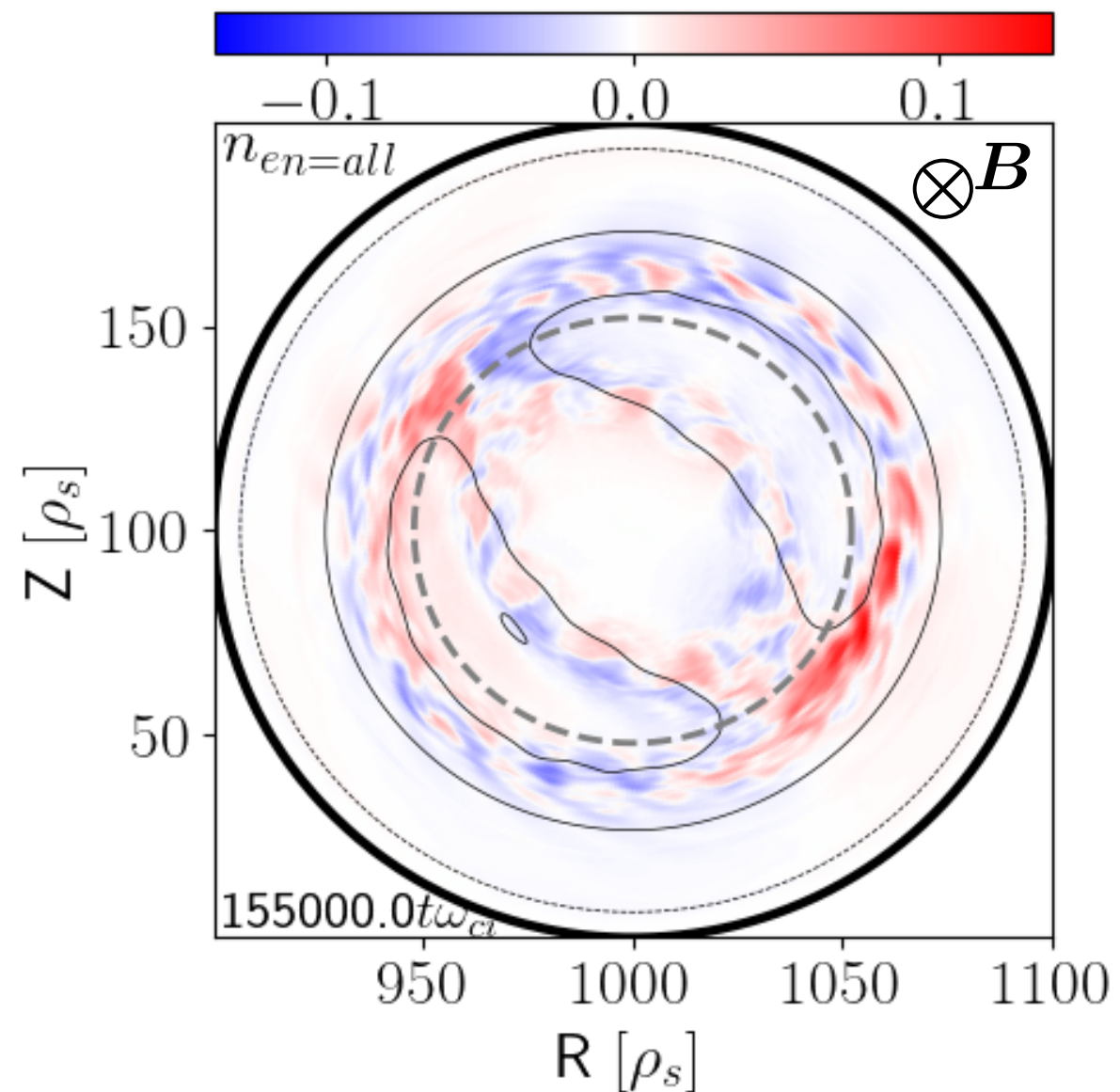
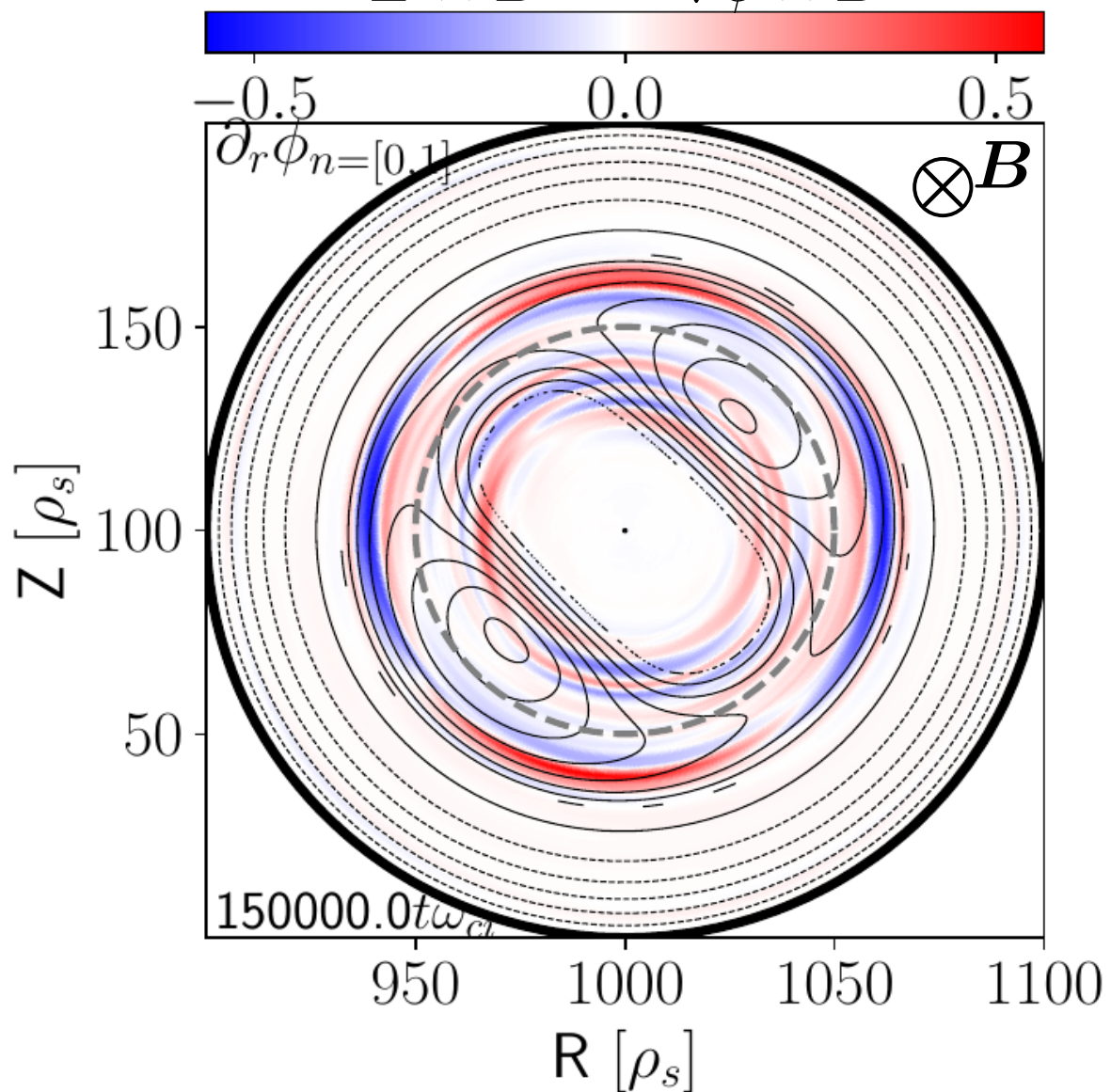
[1] Biskamp 00
[2] Kleva PoP 95



Kelvin-Helmholtz Instability (KHI) and Flows Redistribution

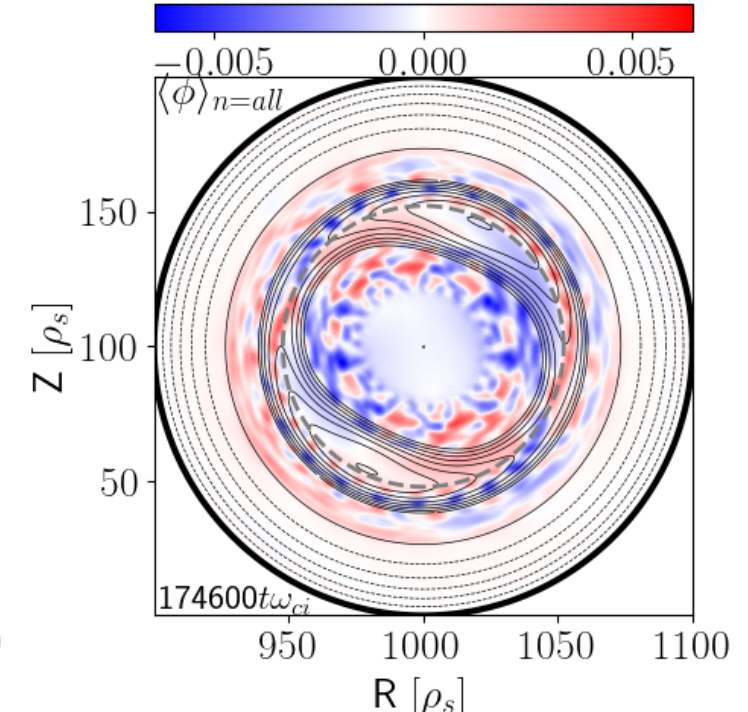
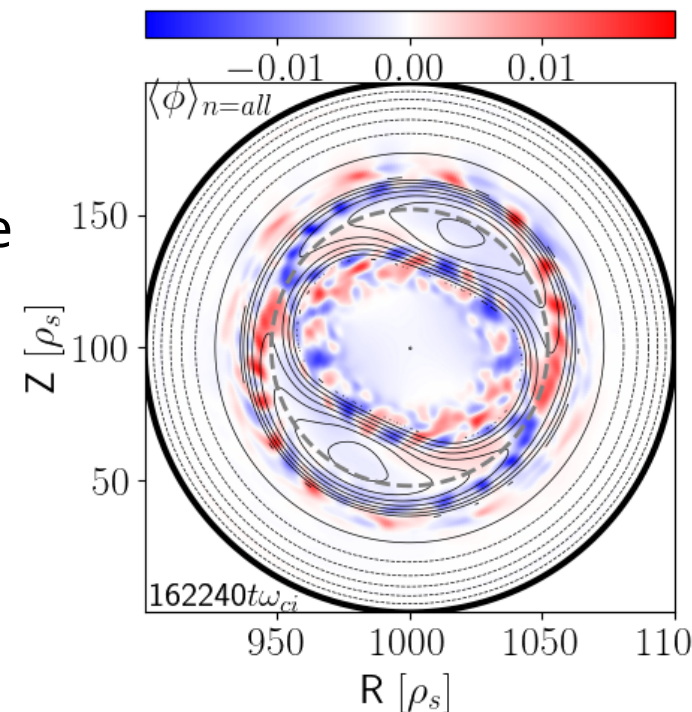
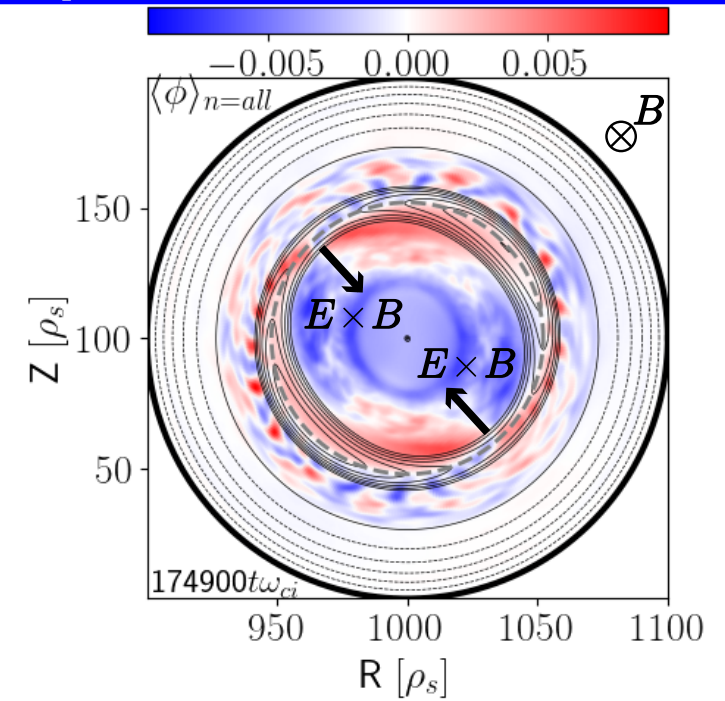
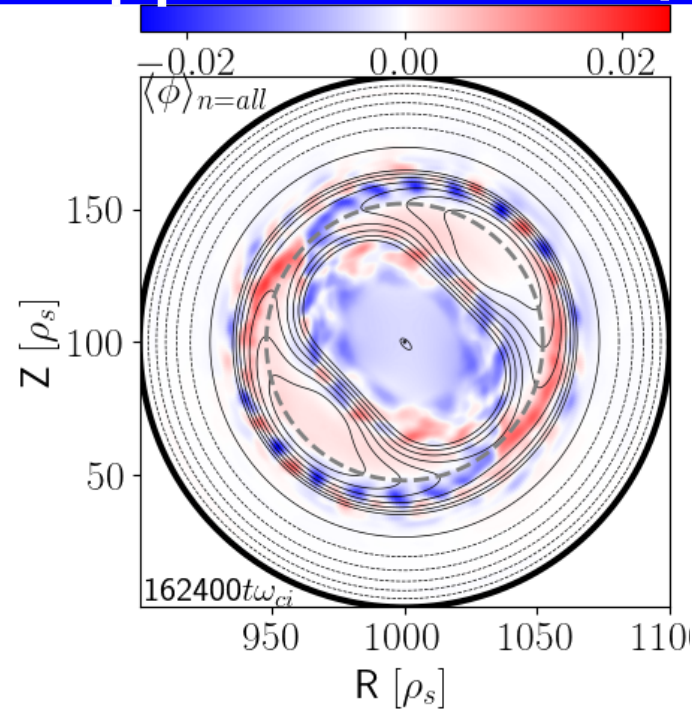
- Large islands induce strong quadrupolar sheared flows
- Localised density and ϕ unstable to KHI [3] Granier PoP 24

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



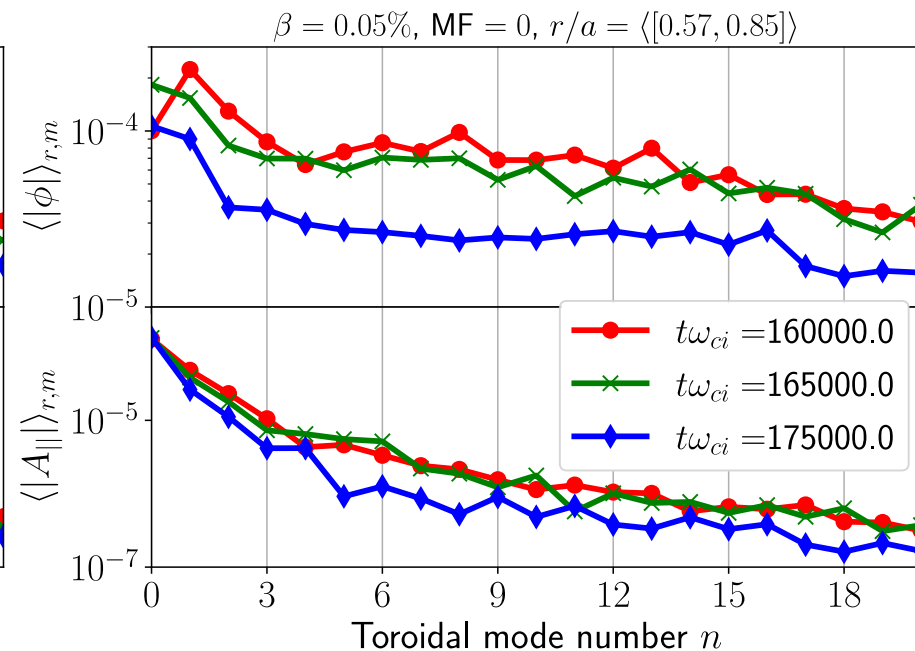
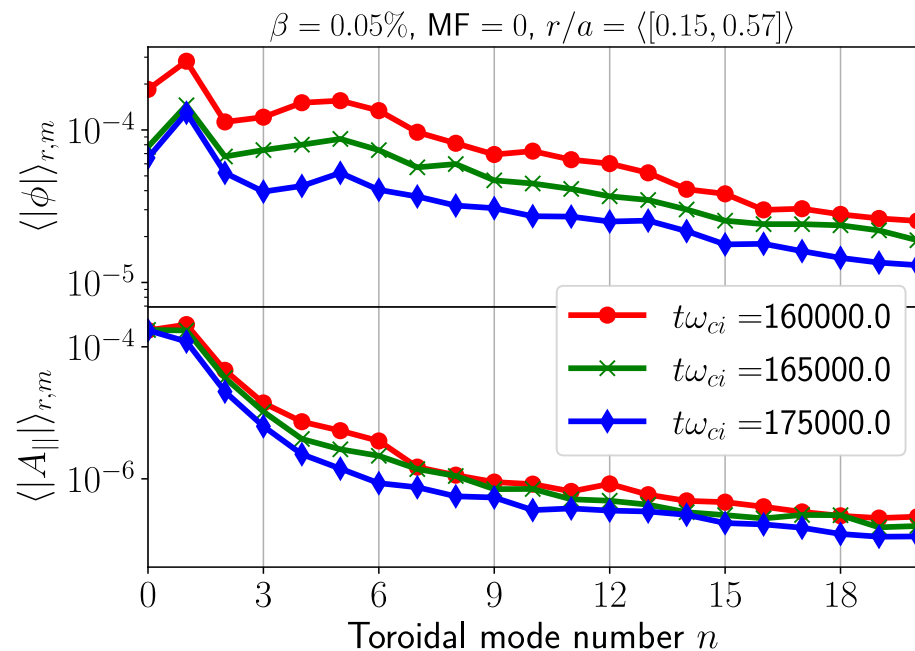
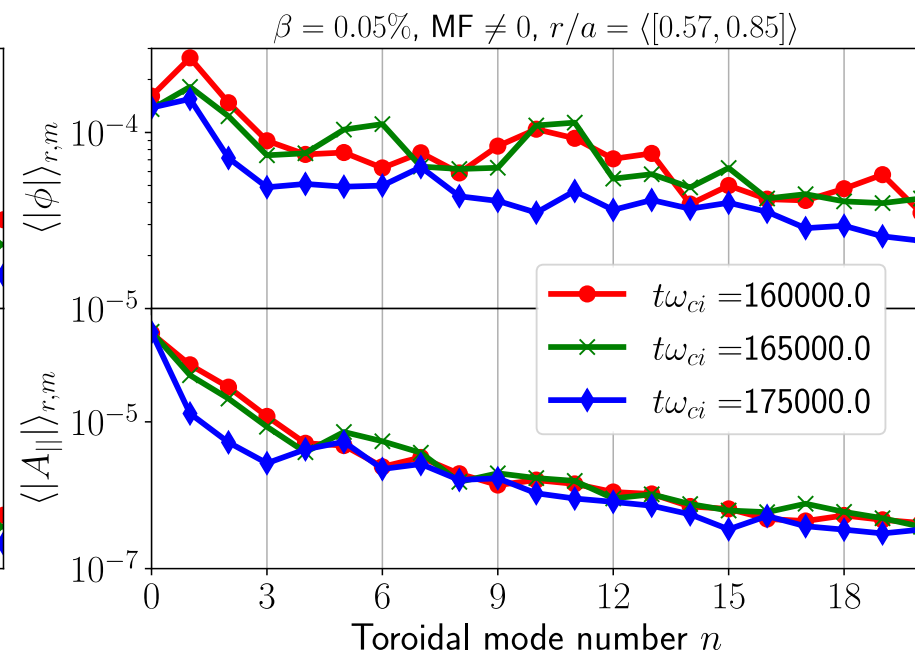
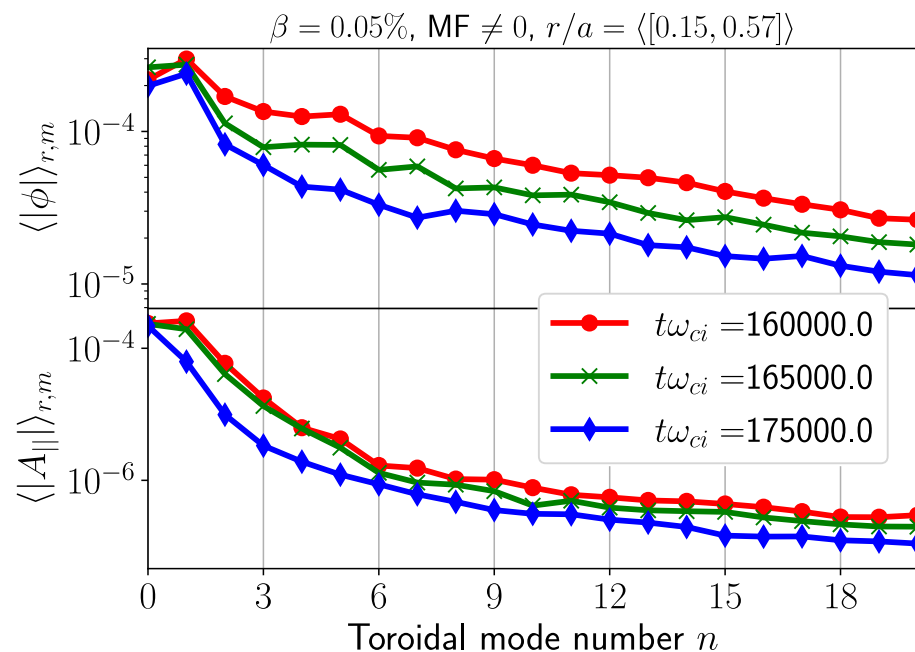
Impacts of Trapped Electrons (TE) I

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



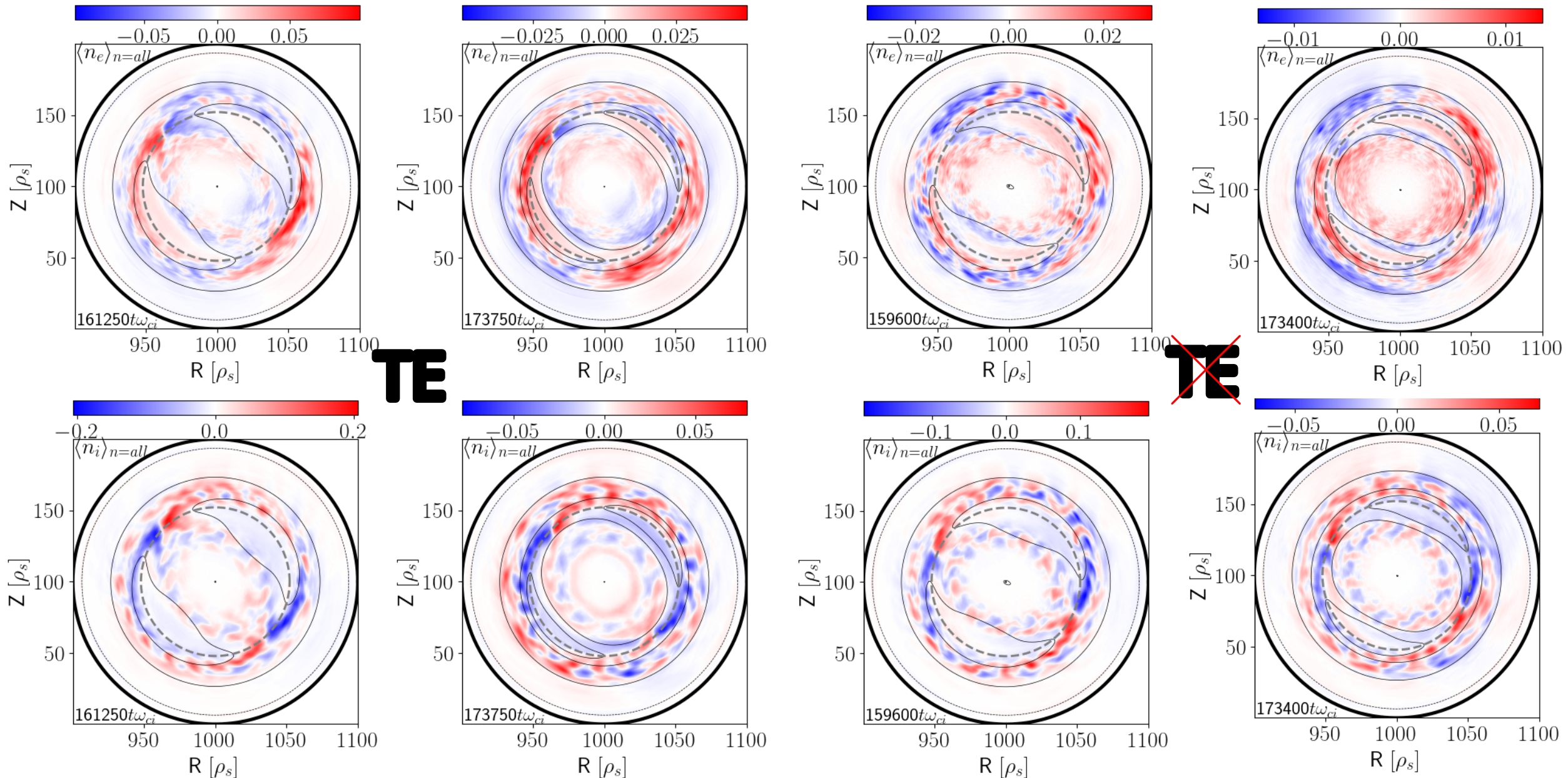
Impacts of Trapped Electrons (TE) II

- 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 $E \times B$ 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 $A_{||}(m = 0, n = 0)$ 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

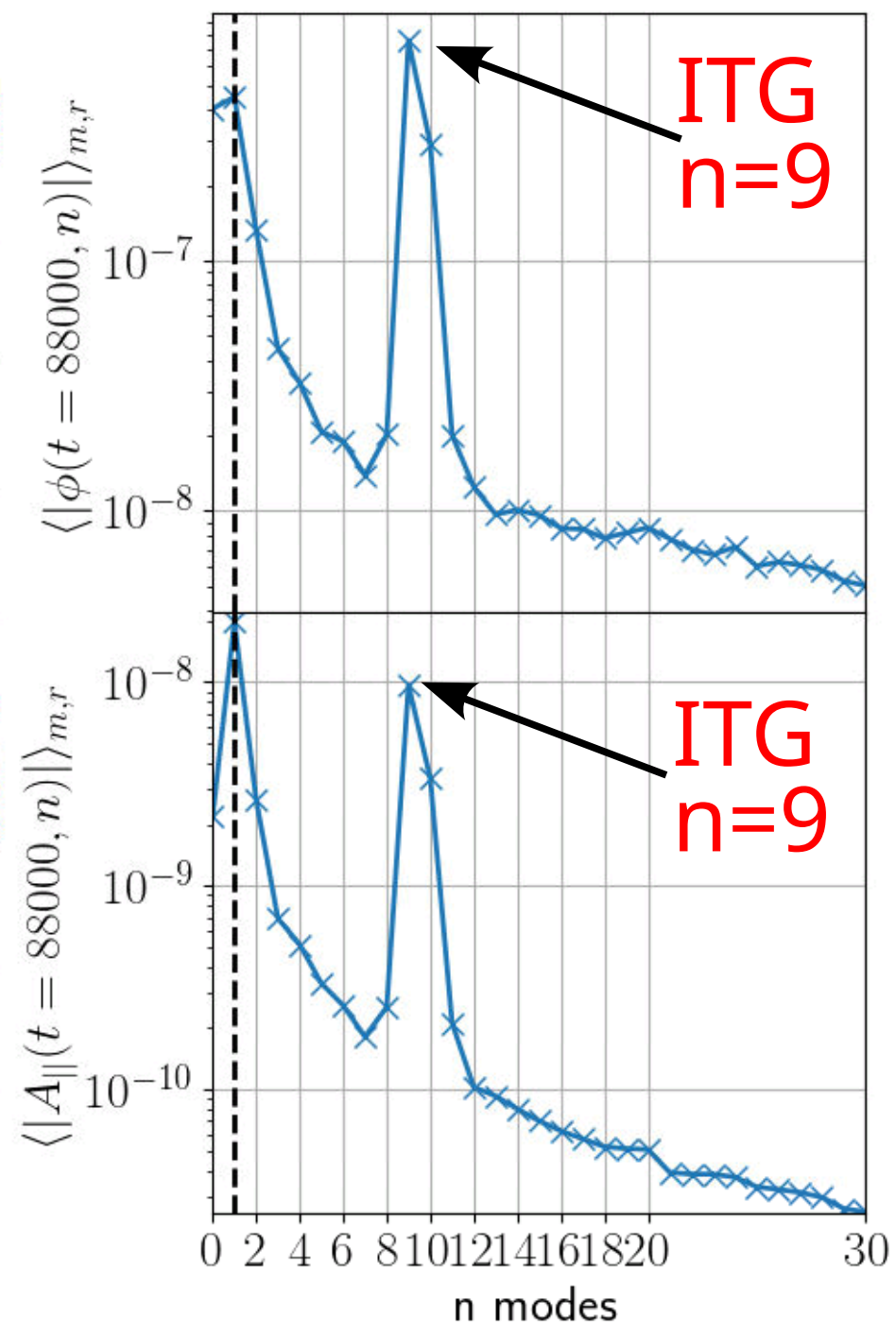
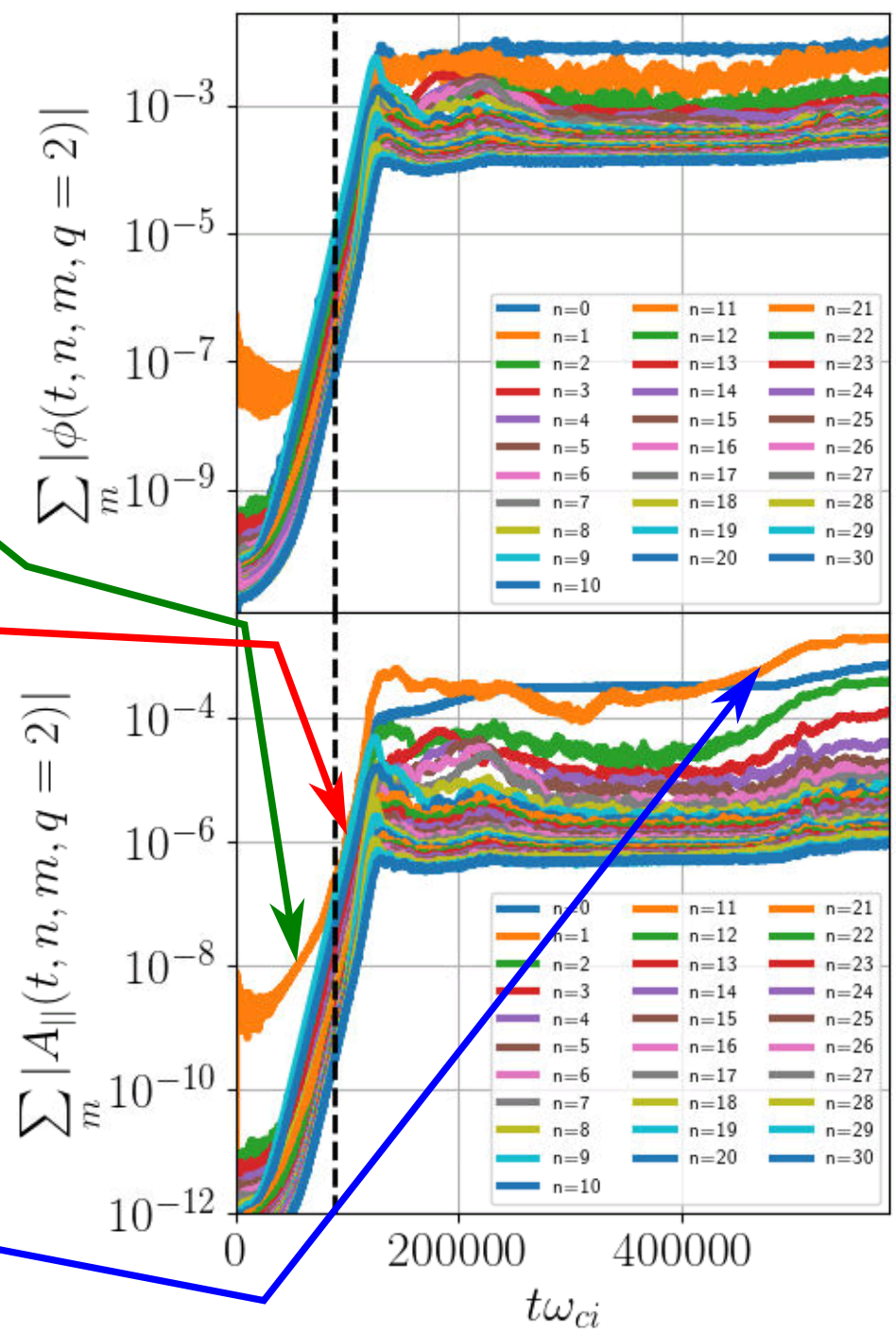
This scenario can be of interest for strongly driven magnetic reconnection like sawtooth events

Tearing Linear Growth Enhanced by Turbulence

Linear TM growth

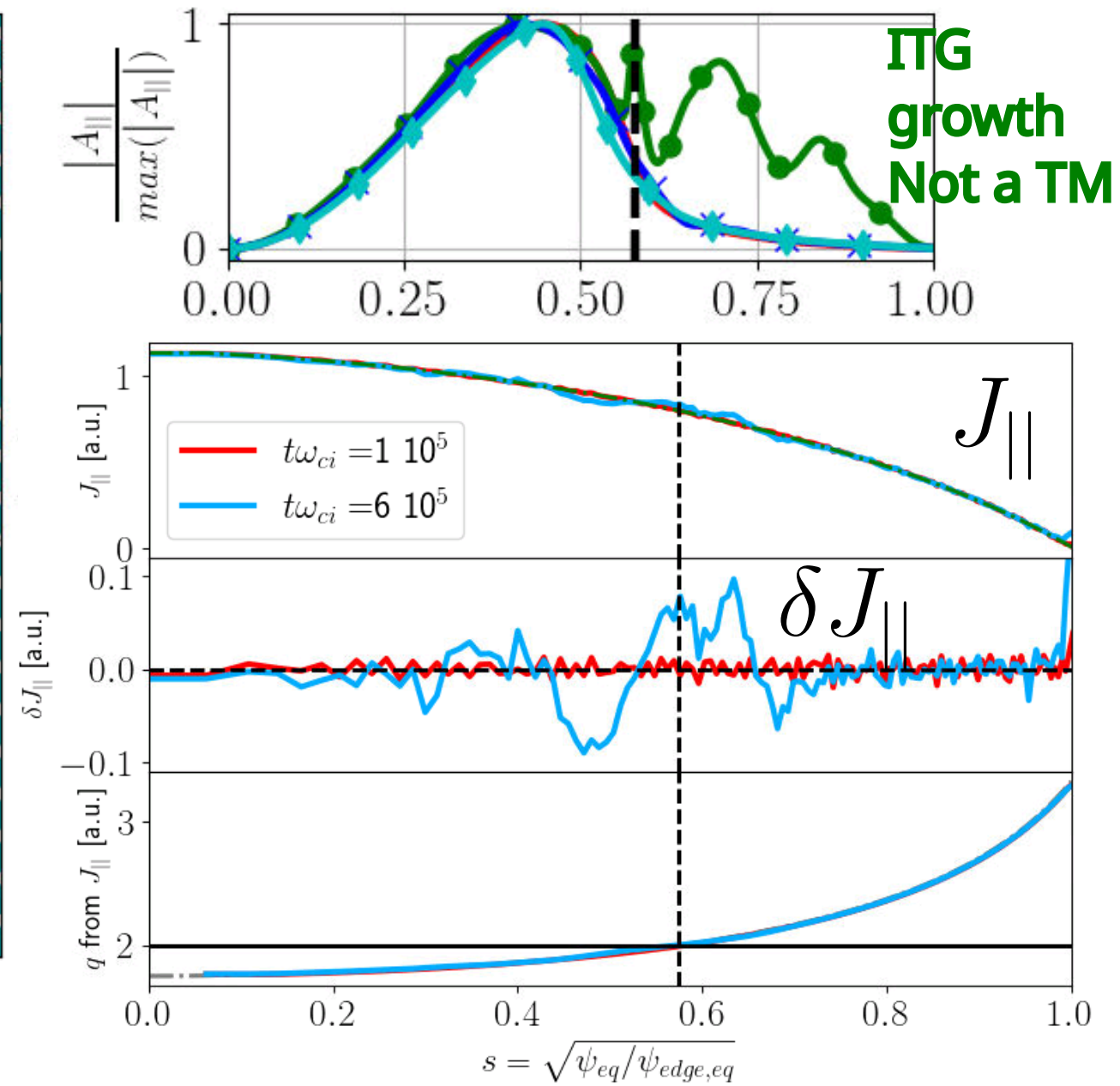
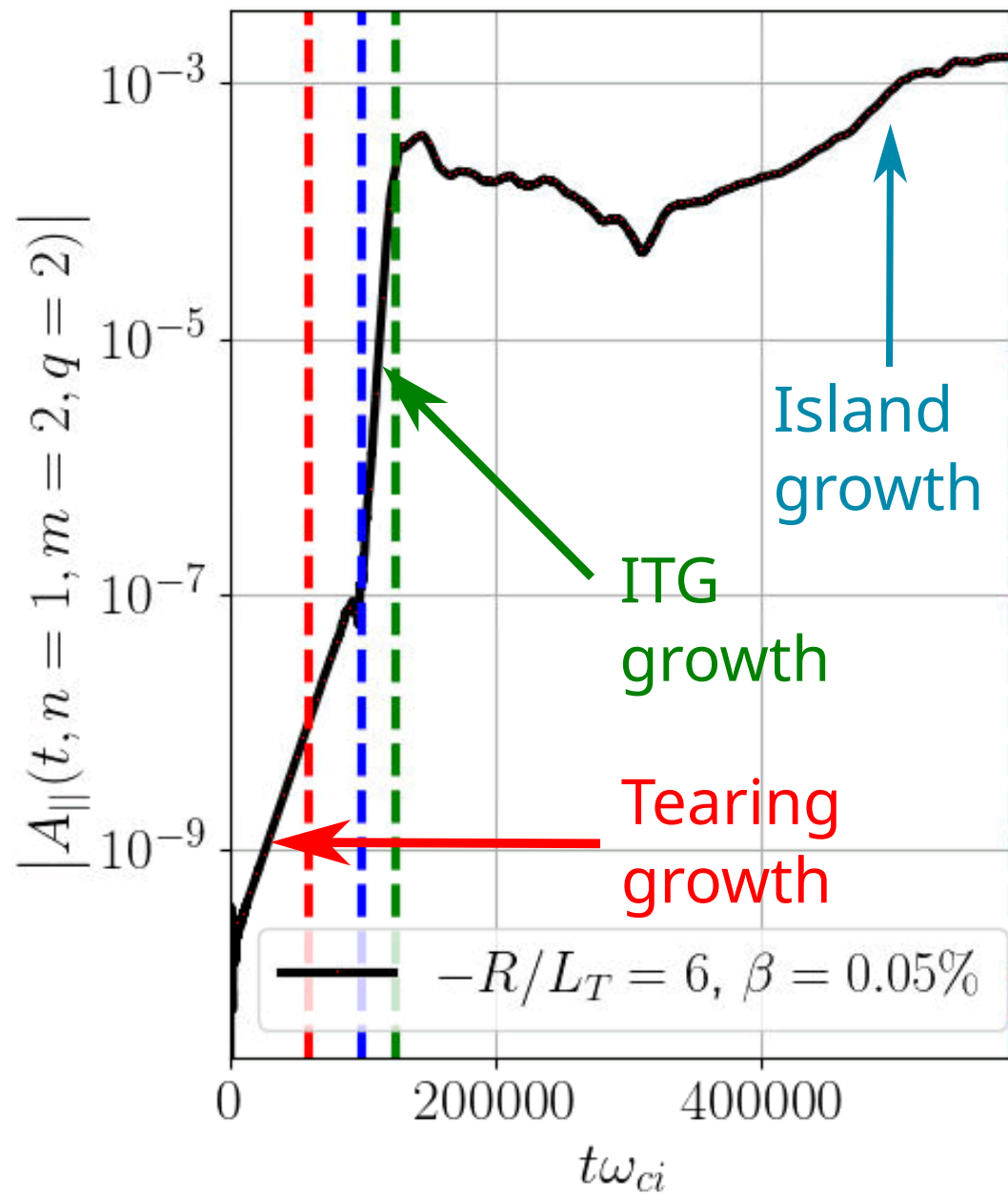
Enhanced growth due to ITG turbulence (Not TM structure)

Island growth from turbulence

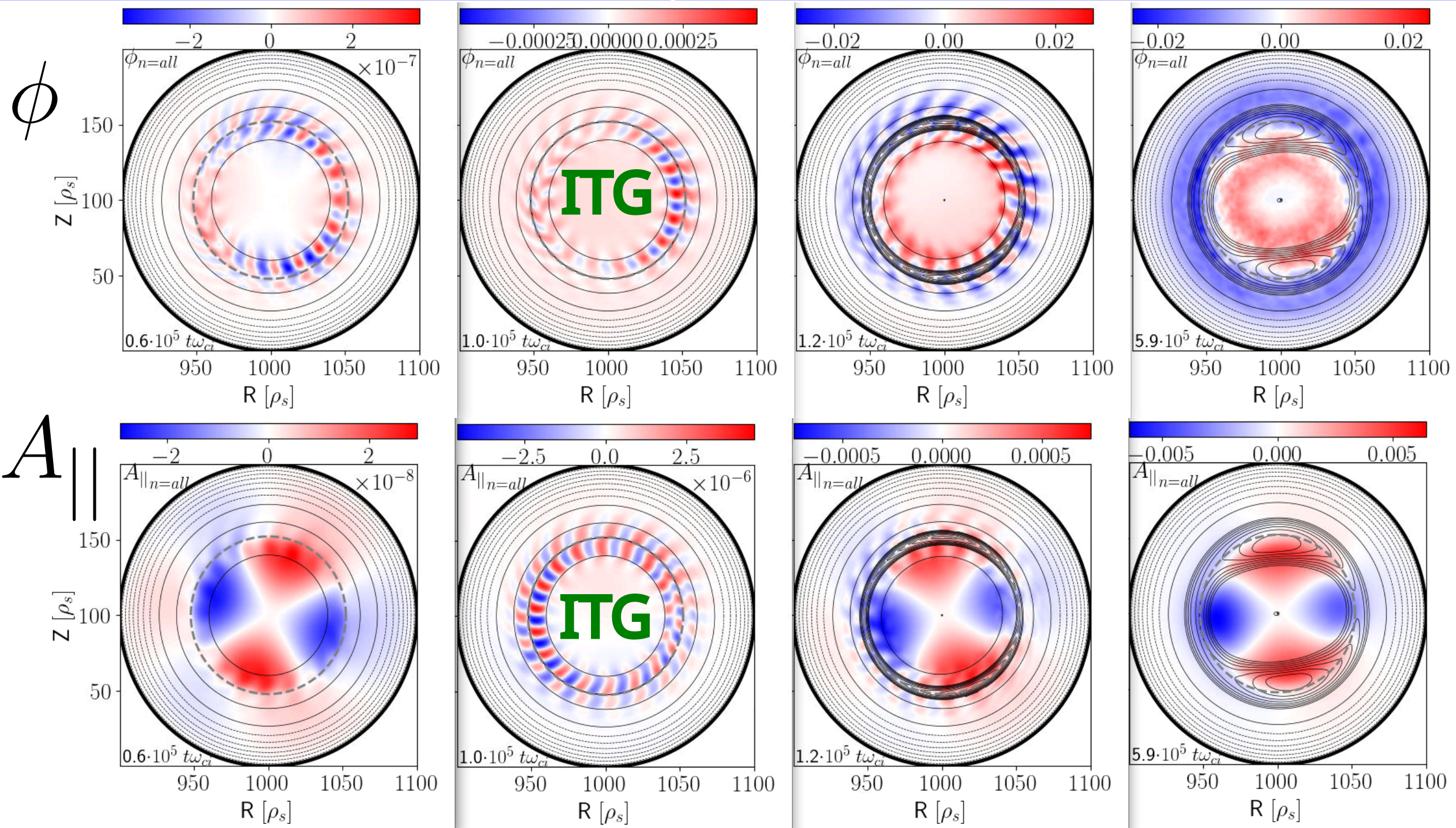


Mode Structure Destroyed by ITG mode n=9

Mode 2/1 dragged by ITG, but not a tearing structure during ITG growth phase.



Contour plots $-R/L_T=6$



Contour plots $n=0$ - $R/L_T=6$

