Island-Turbulence interactions and Role of Zonal Flows

Fabien Widmer[1,a]

[1] Headquarter for Co-Creation Strategy

[1] National Institutes of Natural Sciences
自然科学研究機構

[1] IRCC AFP
International Research Collaboration Center
Astro-Fusion Plasma Unit

[a] *Guest researcher at*
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

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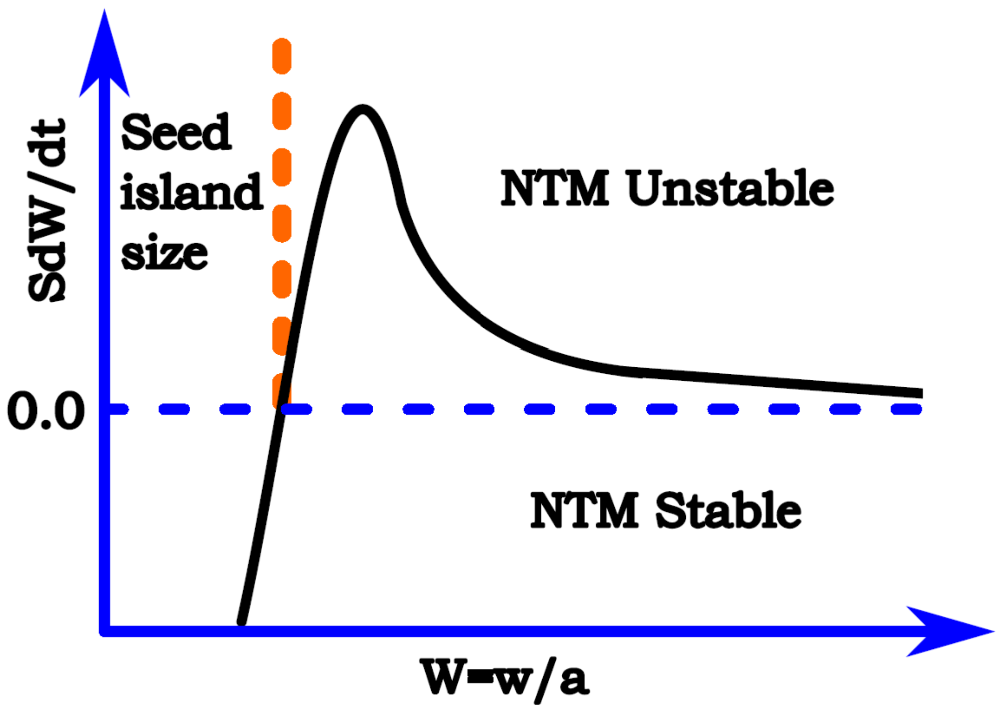
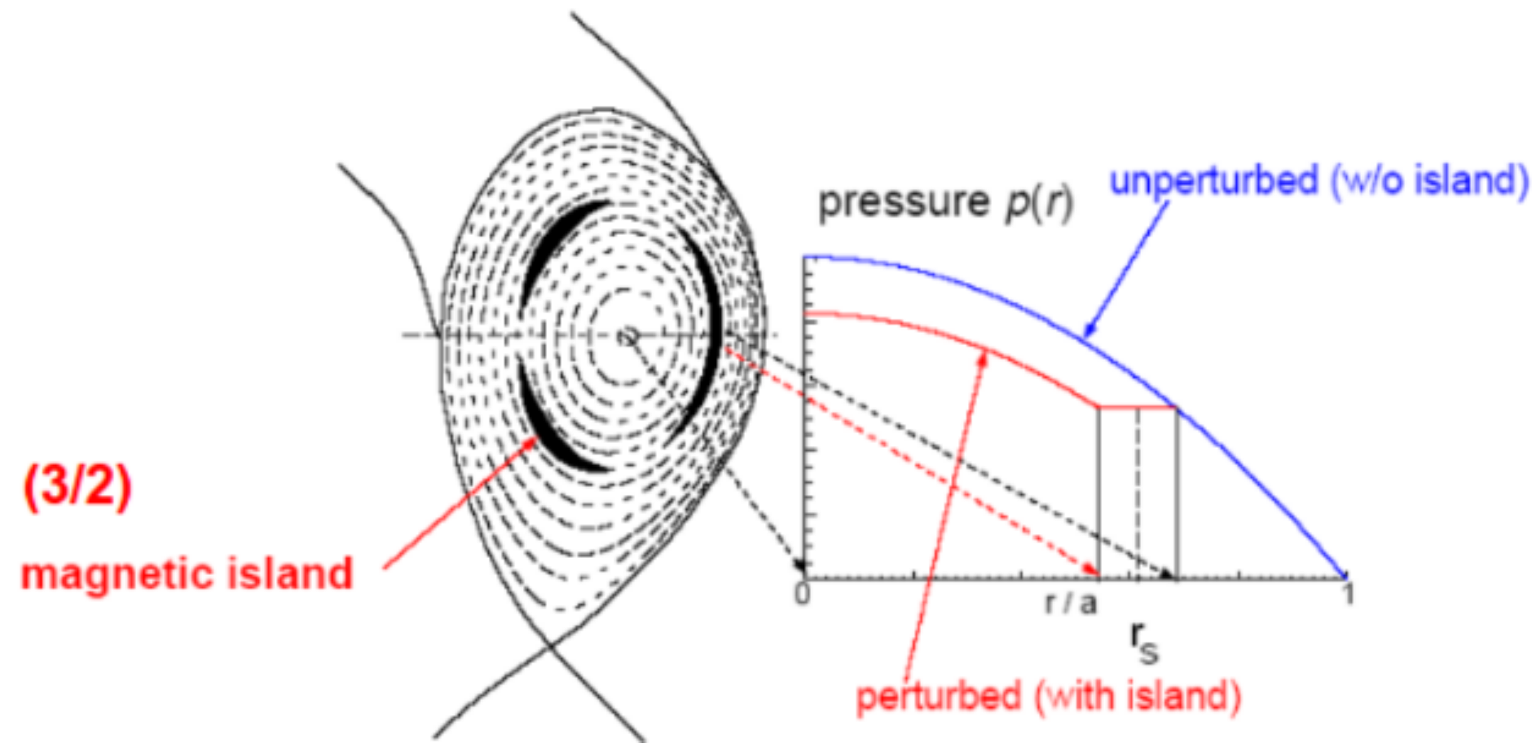
Introduction: NTM Problem

- 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 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)

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



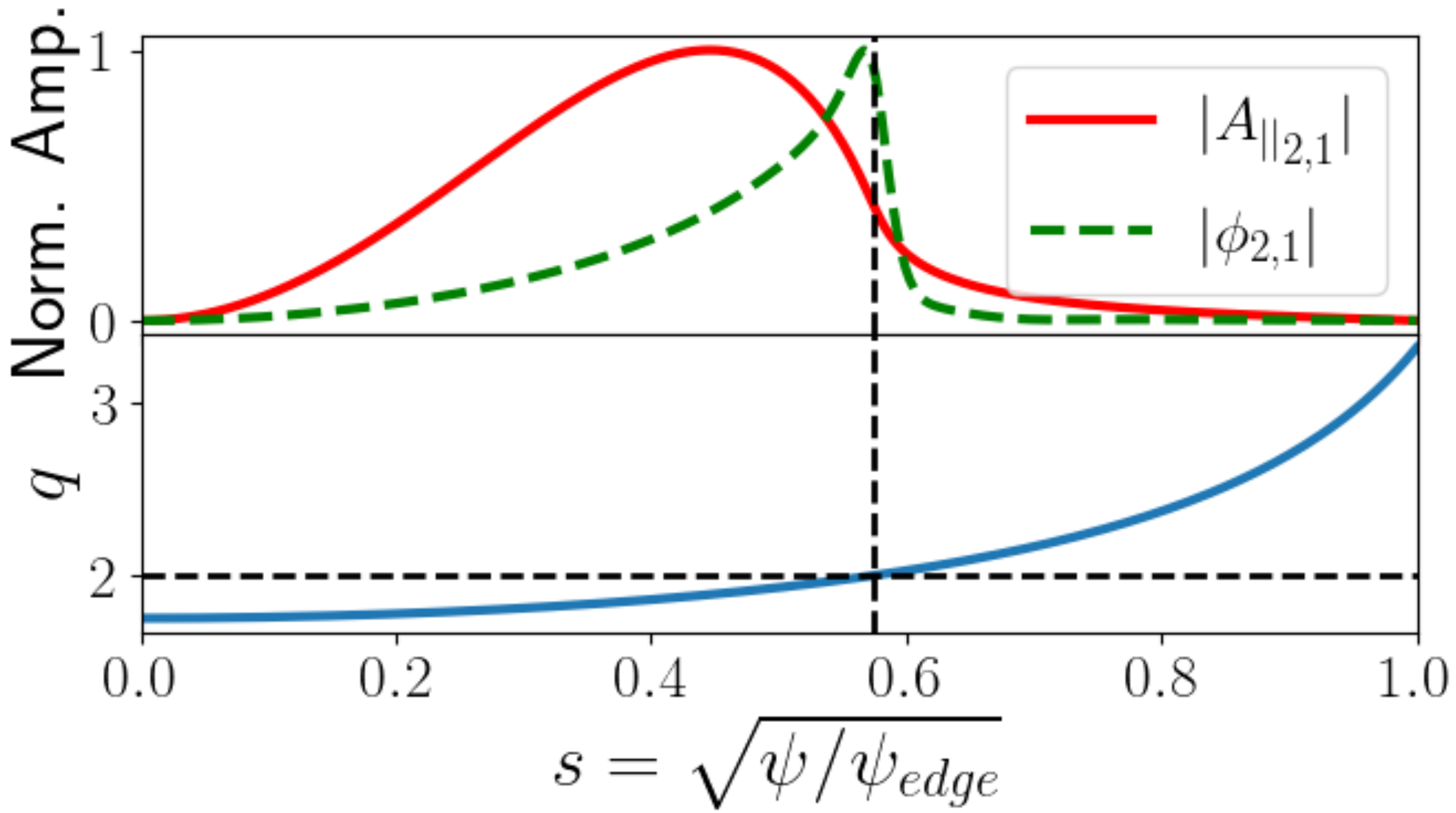


Initial unstable current profile (Wesson 2011)

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

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

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

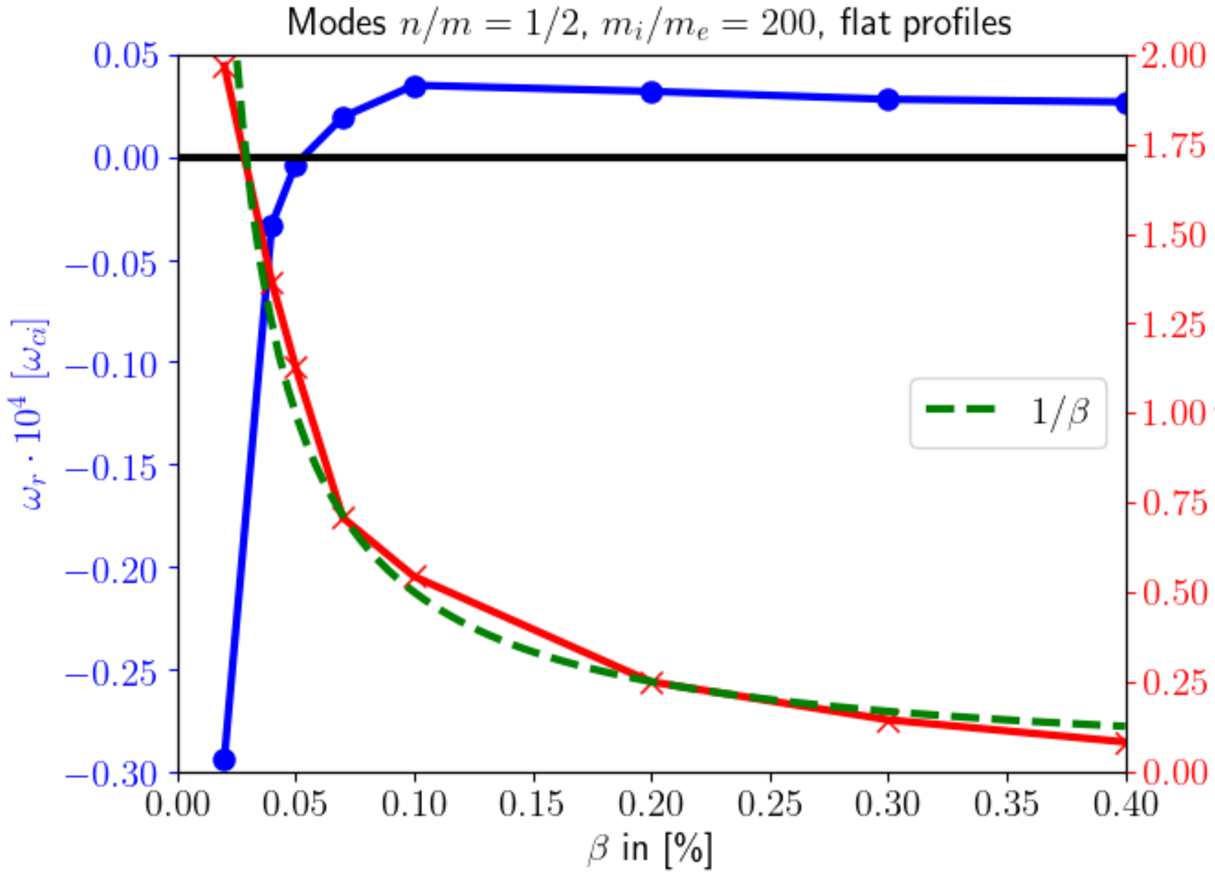


Tearing Mode Validation with ORB5

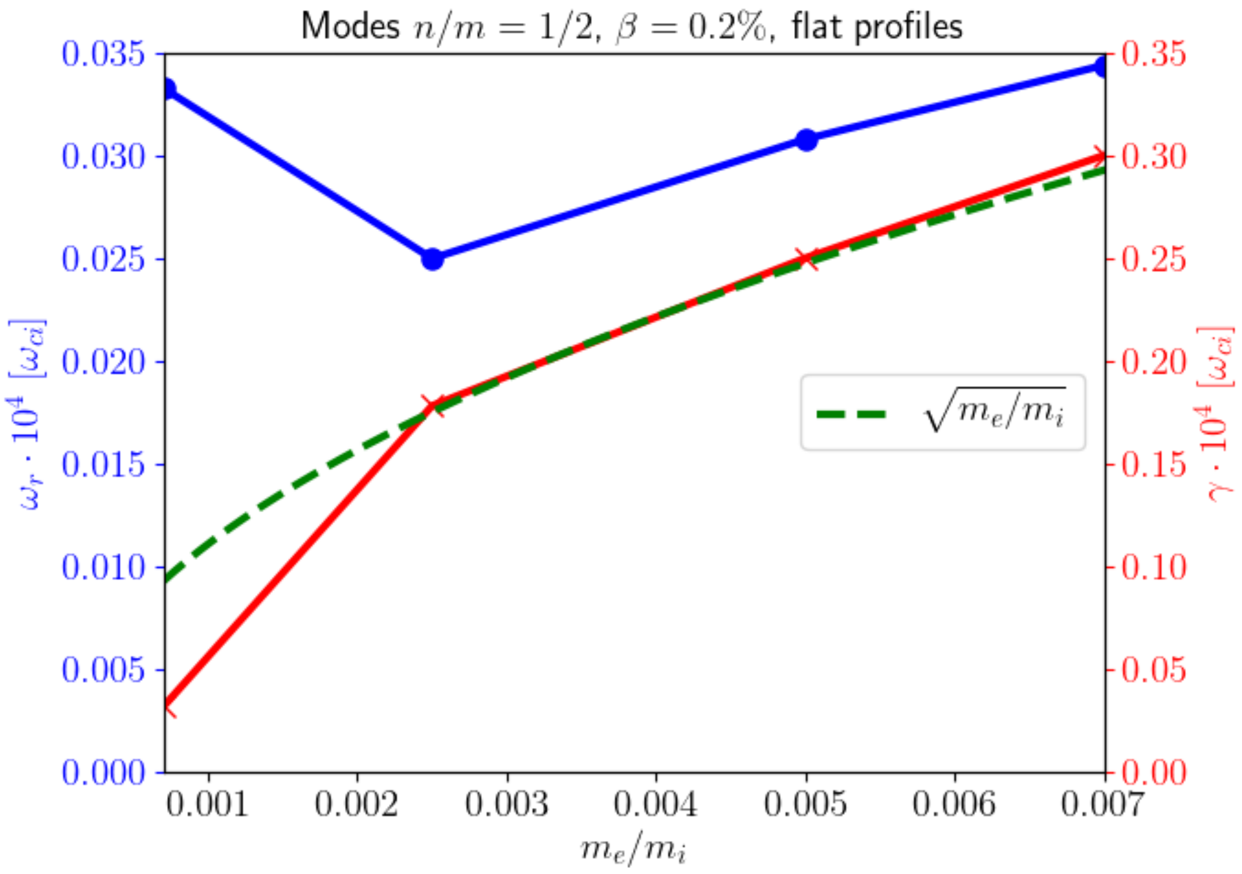
- Kinetic estimation of the growth rate (Rogers 2007)
- $\gamma_{cl}/\gamma_{ci} = \Delta' \rho_{se} k_\theta \rho_{se} \left(\frac{m_e}{m_i}\right)^{1/2} \frac{1}{T_e^{1/2}} (T_e + T_i)^{1/2} \frac{1}{\beta_e}$ Validity: $m_e/m_i < \beta$

Linear simulations with flat density and temperature profiles in 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%

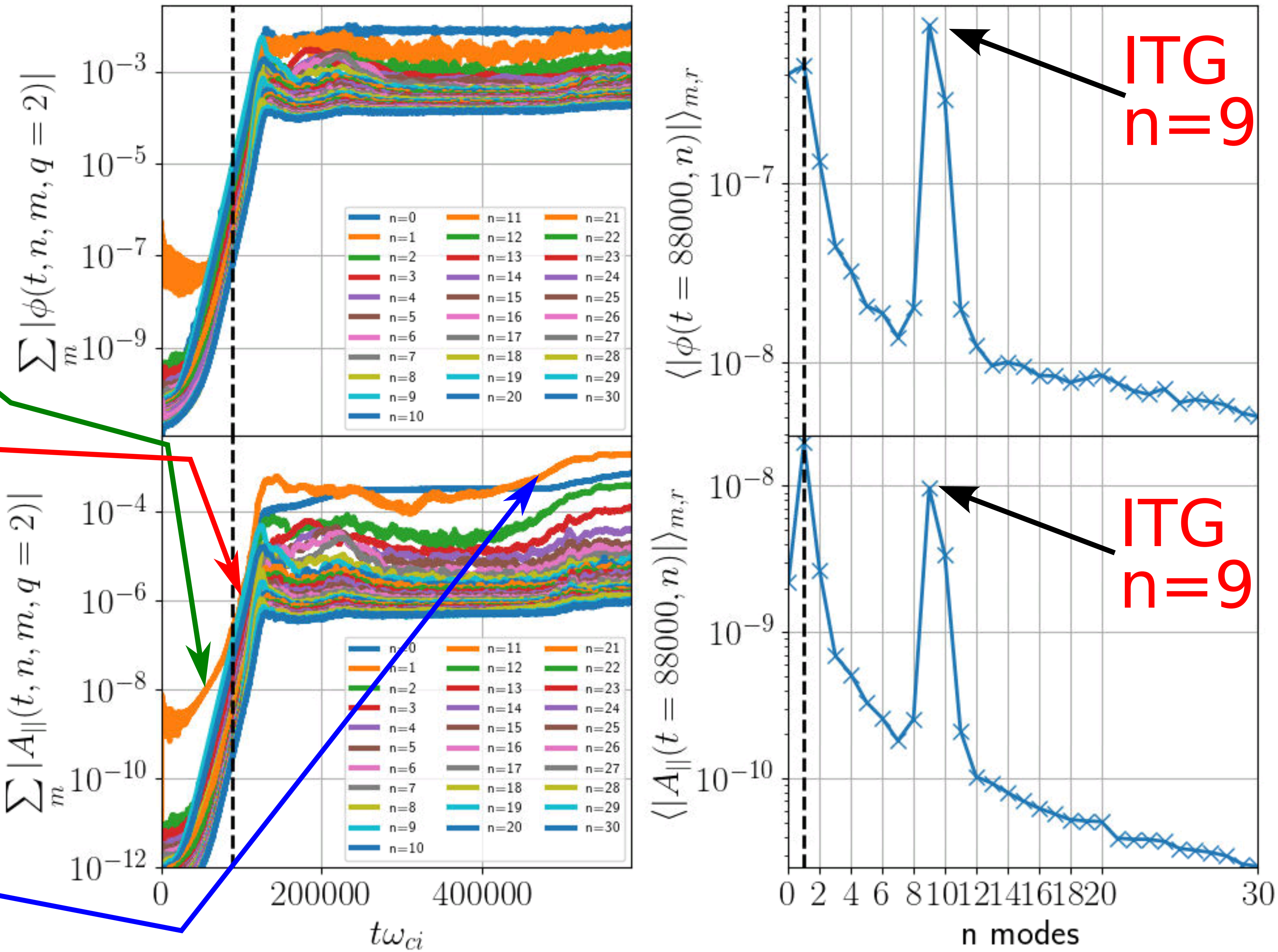


Tearing Linear Growth Enhanced by Turbulence

Linear TM growth

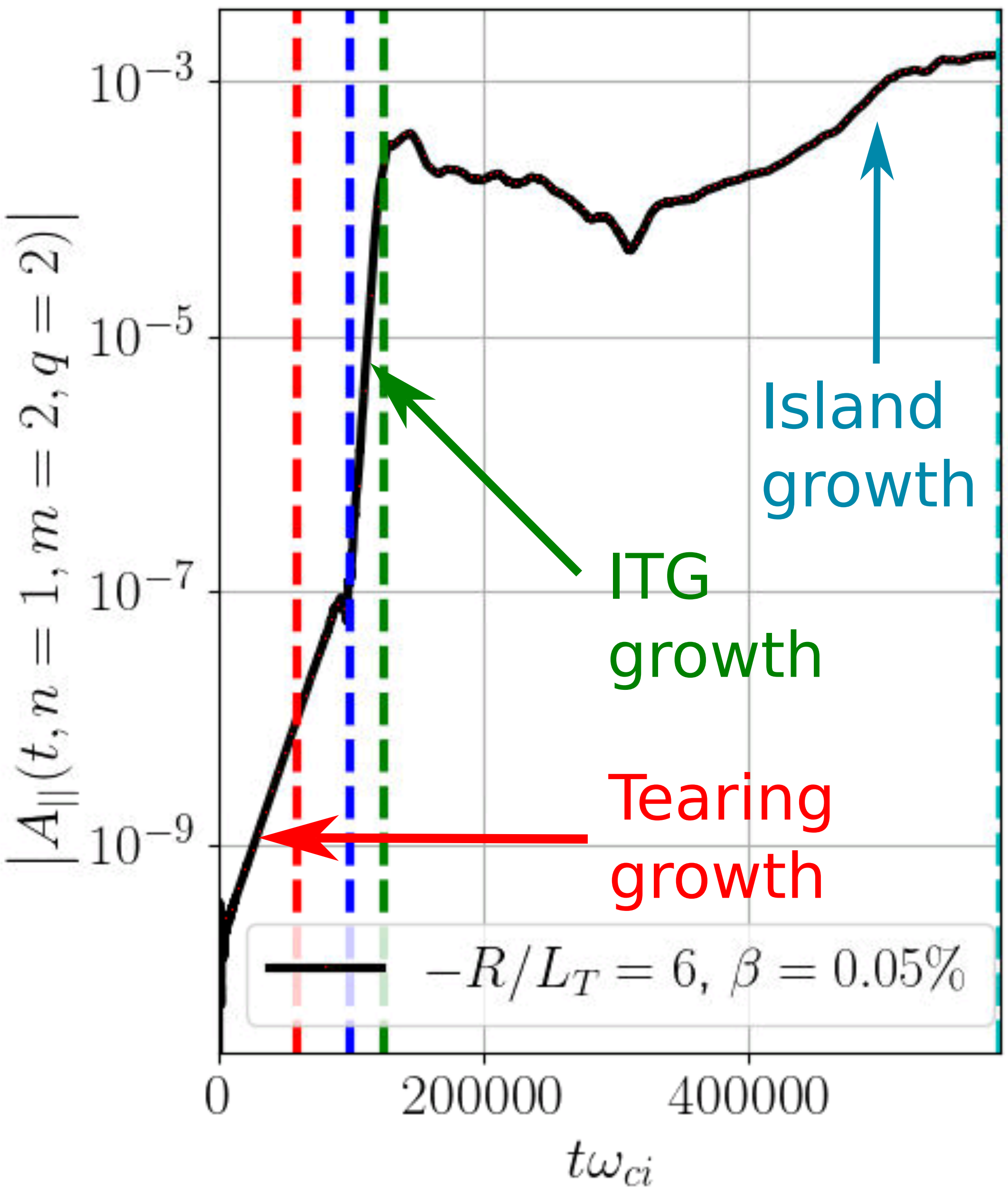
Enhanced growth due to ITG turbulence (Not TM structure)

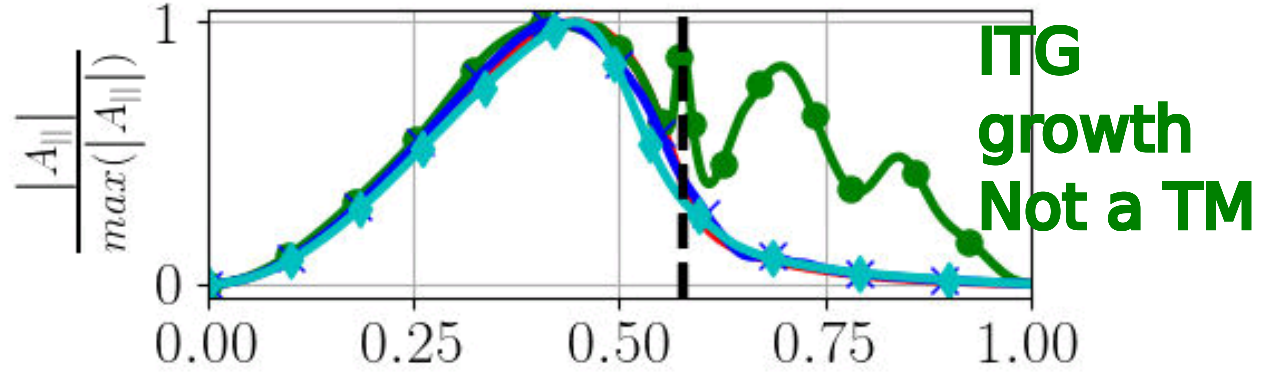
Island growth from turbulence

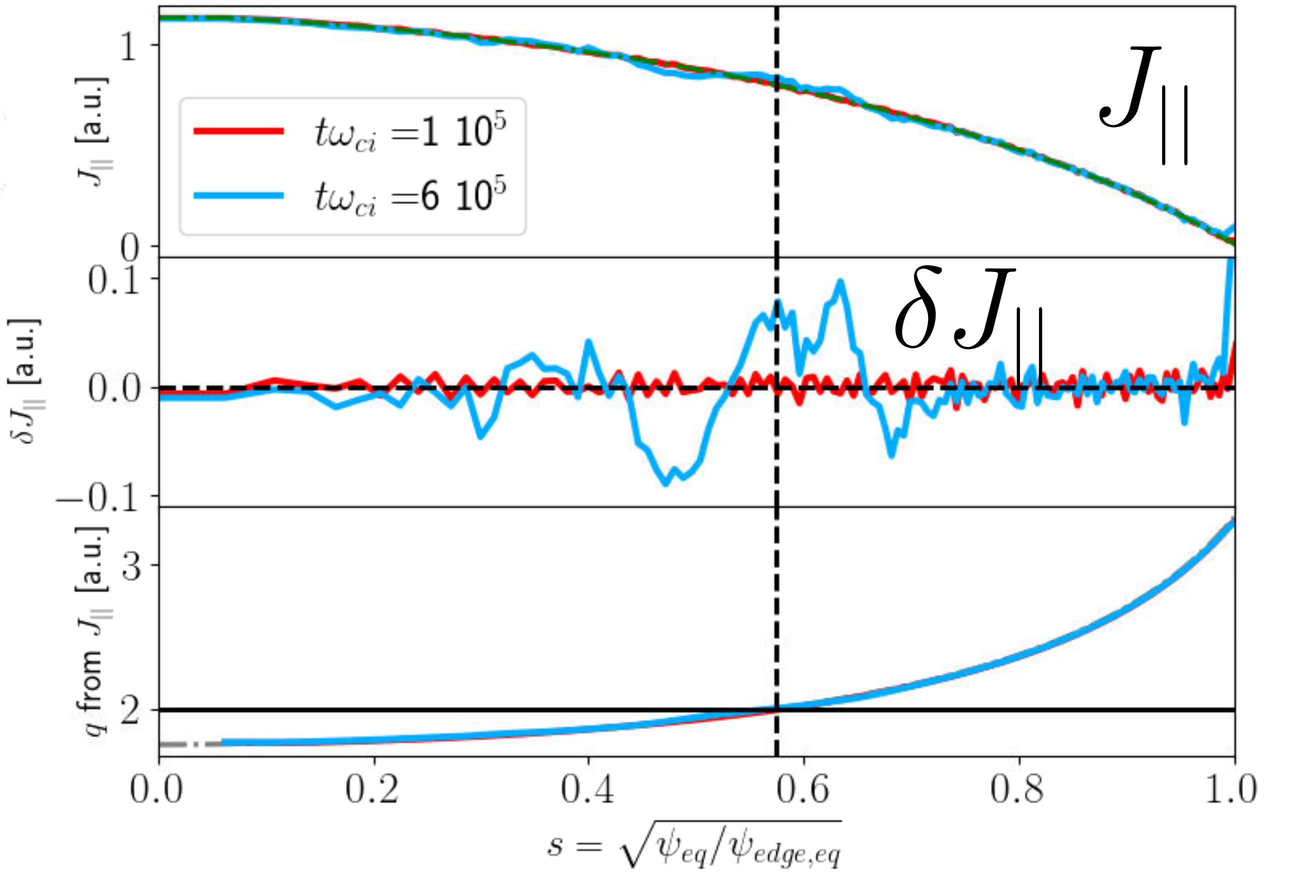


Mode Structure Destroyed by ITG mode n=9

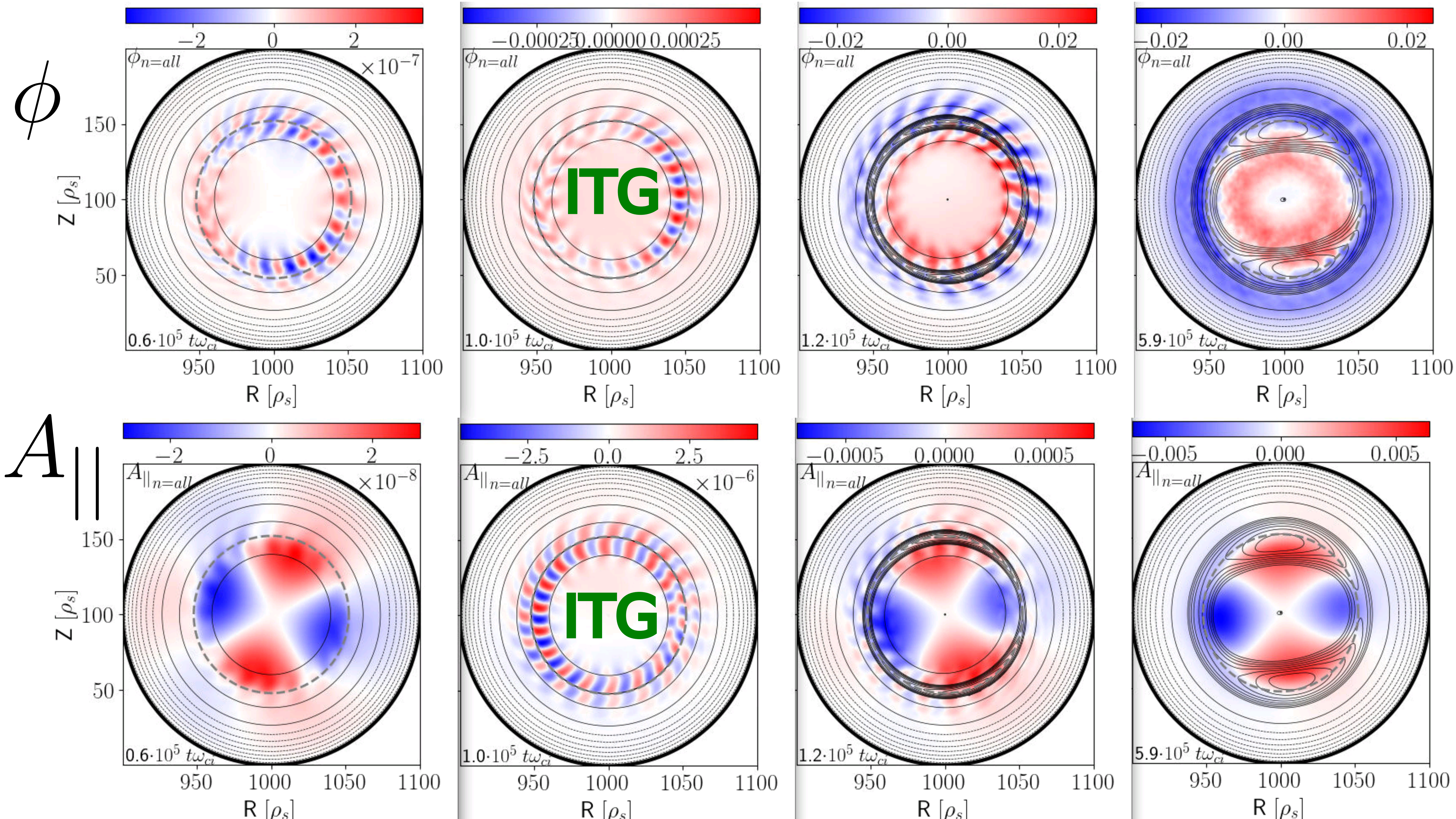
Mode 2/1 dragged by ITG, but not a tearing structure during ITG growth phase.



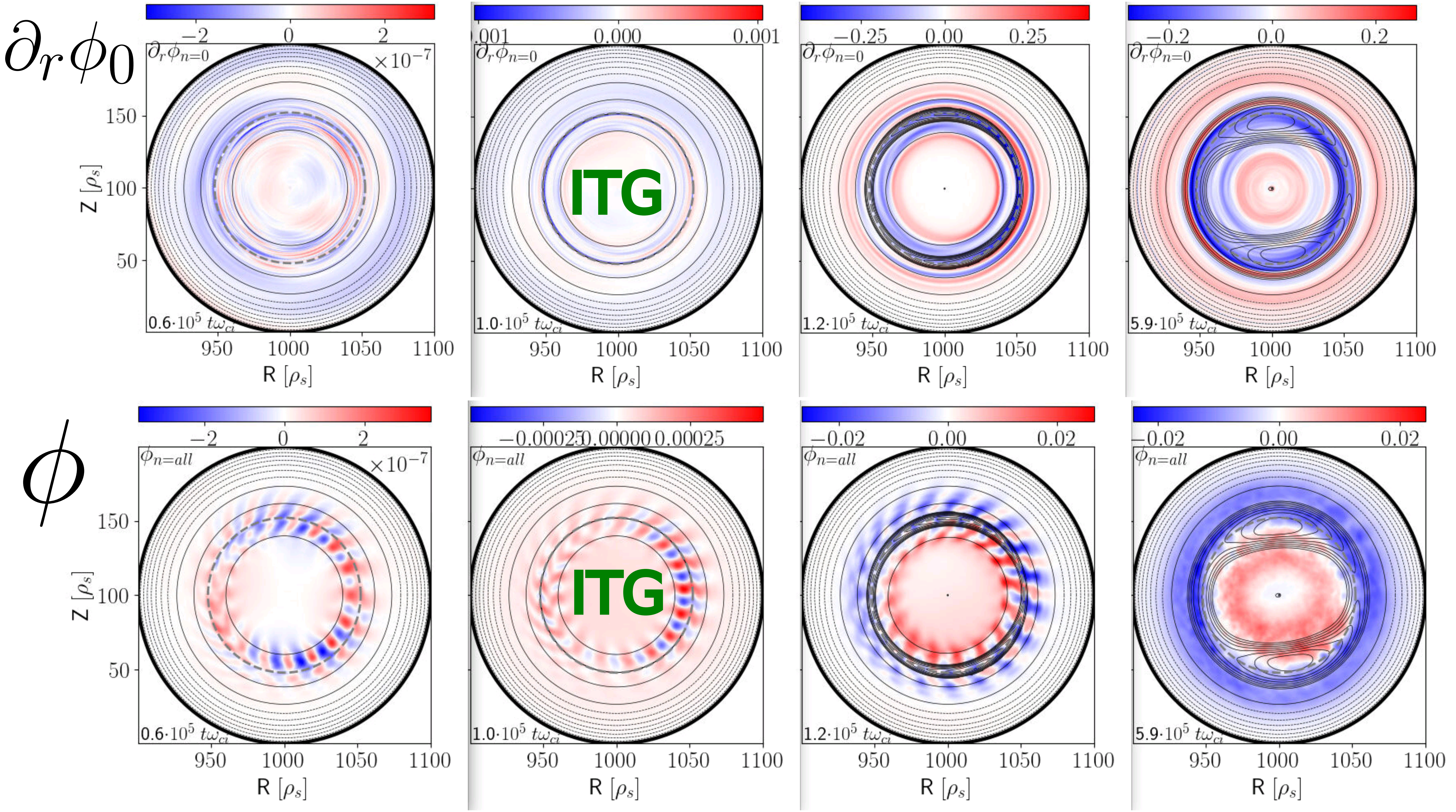




Contour plots $-R/L_T=6$

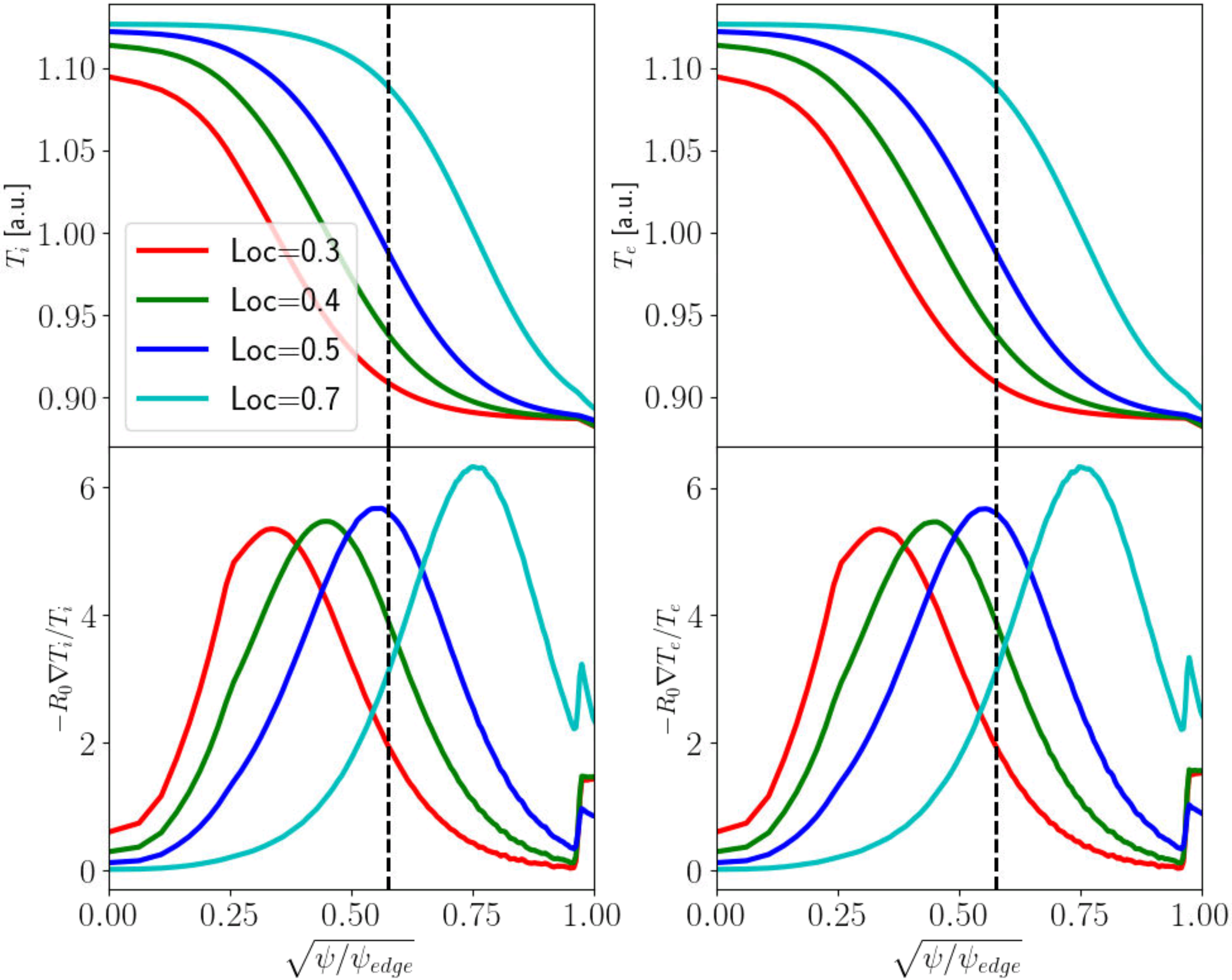


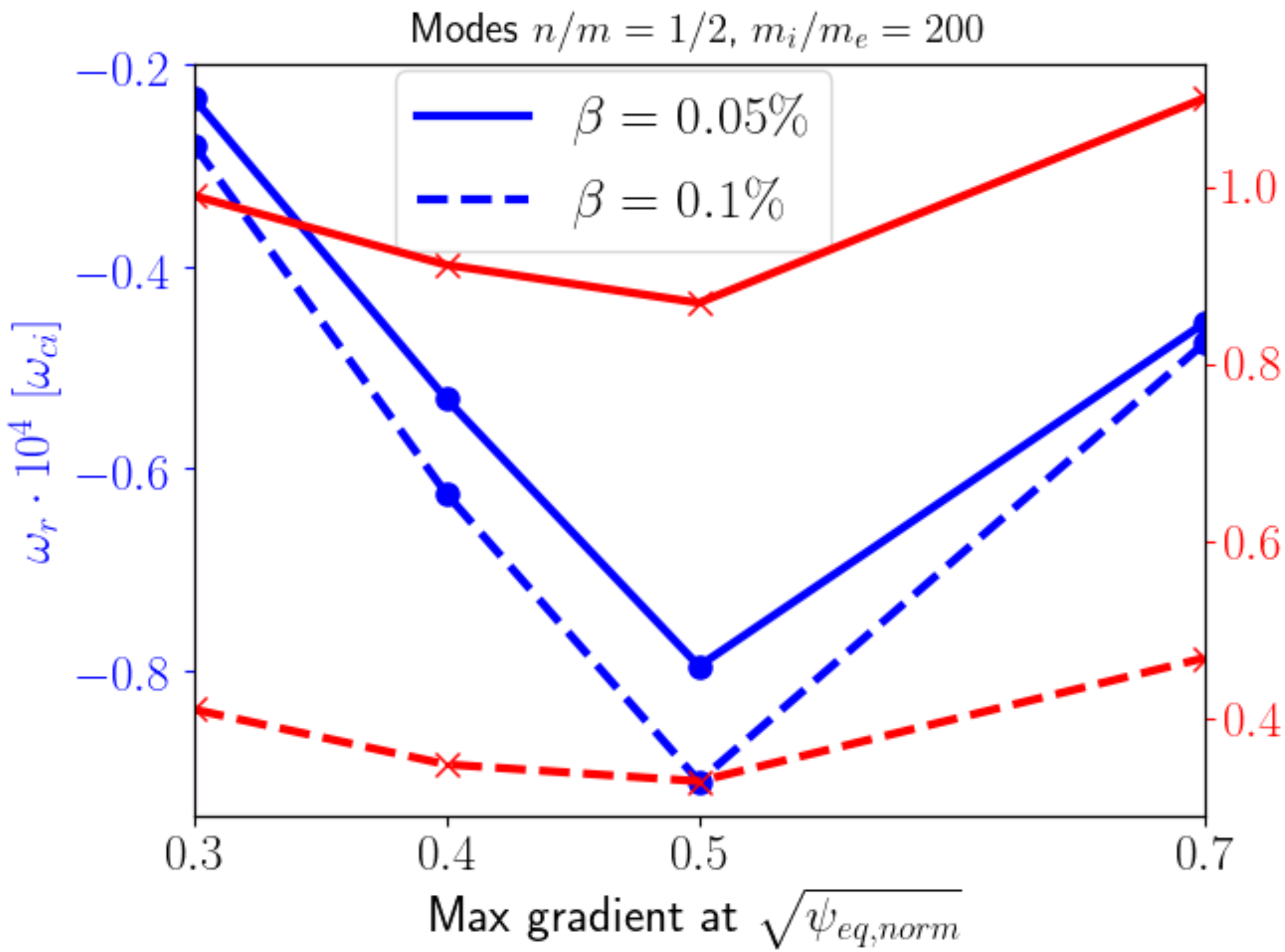
Contour plots n=0 $-R/L_T=6$

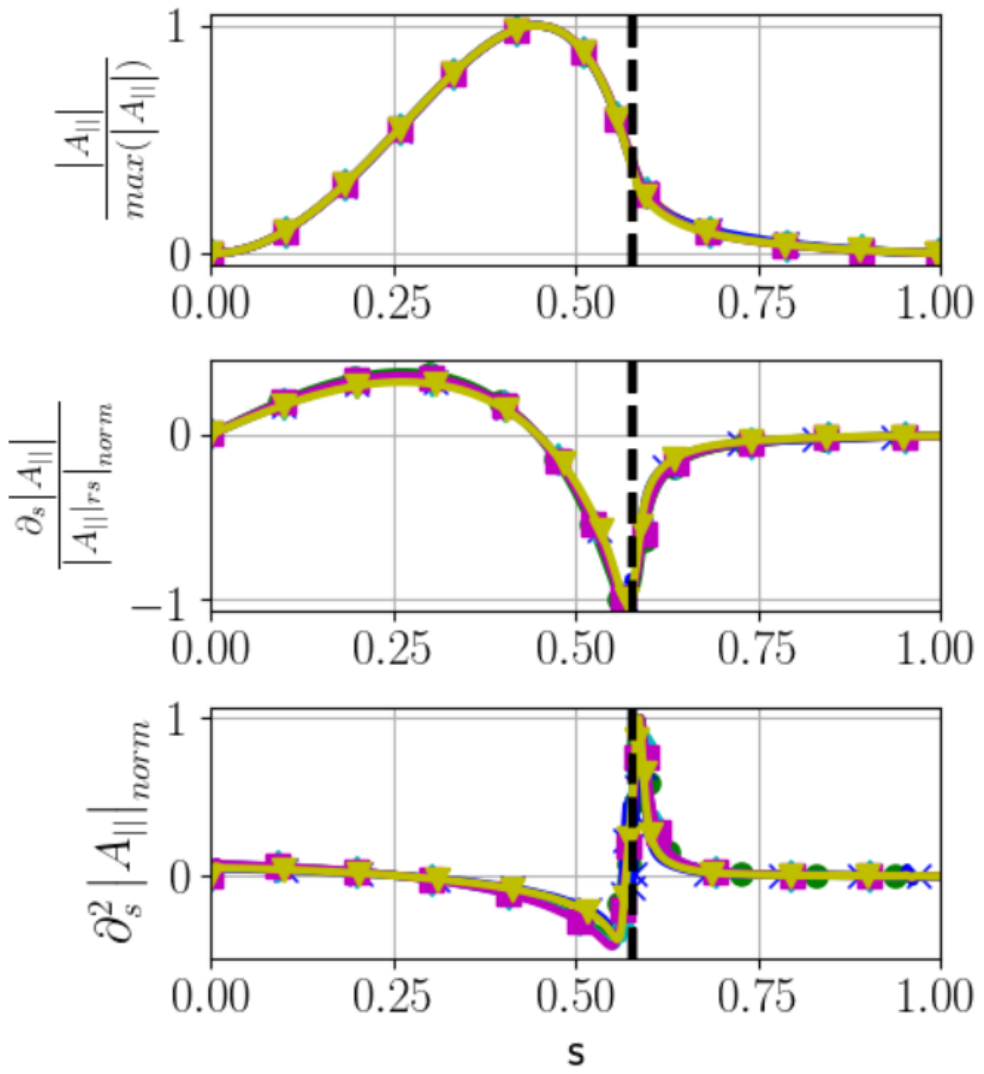


Maximum gradients at different radius and Temrature Profiles

Varying the radial location of the maximum value of the temperature gradient to investigate the mutual interaction turbulence and island on turbulence transport



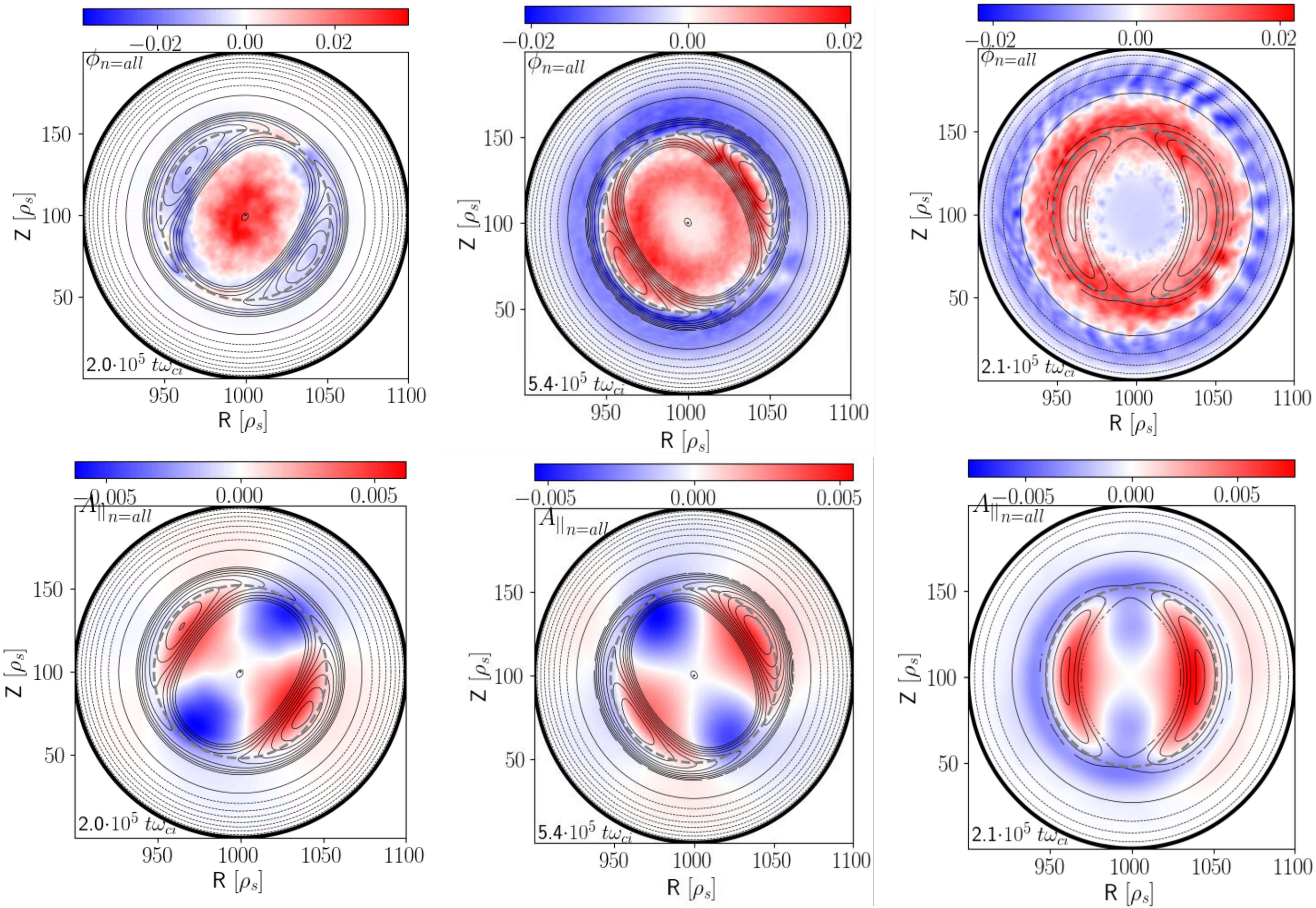

Modes $n/m = 1/2$, $m_i/m_e = 200$
$\beta = 0.05\%$
$\beta = 0.1\%$
-0.2
-0.4
-0.6
-0.8
$\omega_r \cdot 10^4\ [\omega_{ci}]$
1.0
0.8
0.6
0.4
$\gamma \cdot 10^4\ [\omega_{ci}]$
0.3
0.4
0.5
0.7
Max gradient at $\sqrt{\psi_{eq,norm}}$


$\frac{|A_{||}|}{max(|A_{||}|)}$
$\frac{\partial_s |A_{||}|}{|A_{||}|_{rs}}\Big|_{norm}$
$\partial_s^2 |A_{||}|_{norm}$
0.00
0.25
0.50
0.75
1.00
s

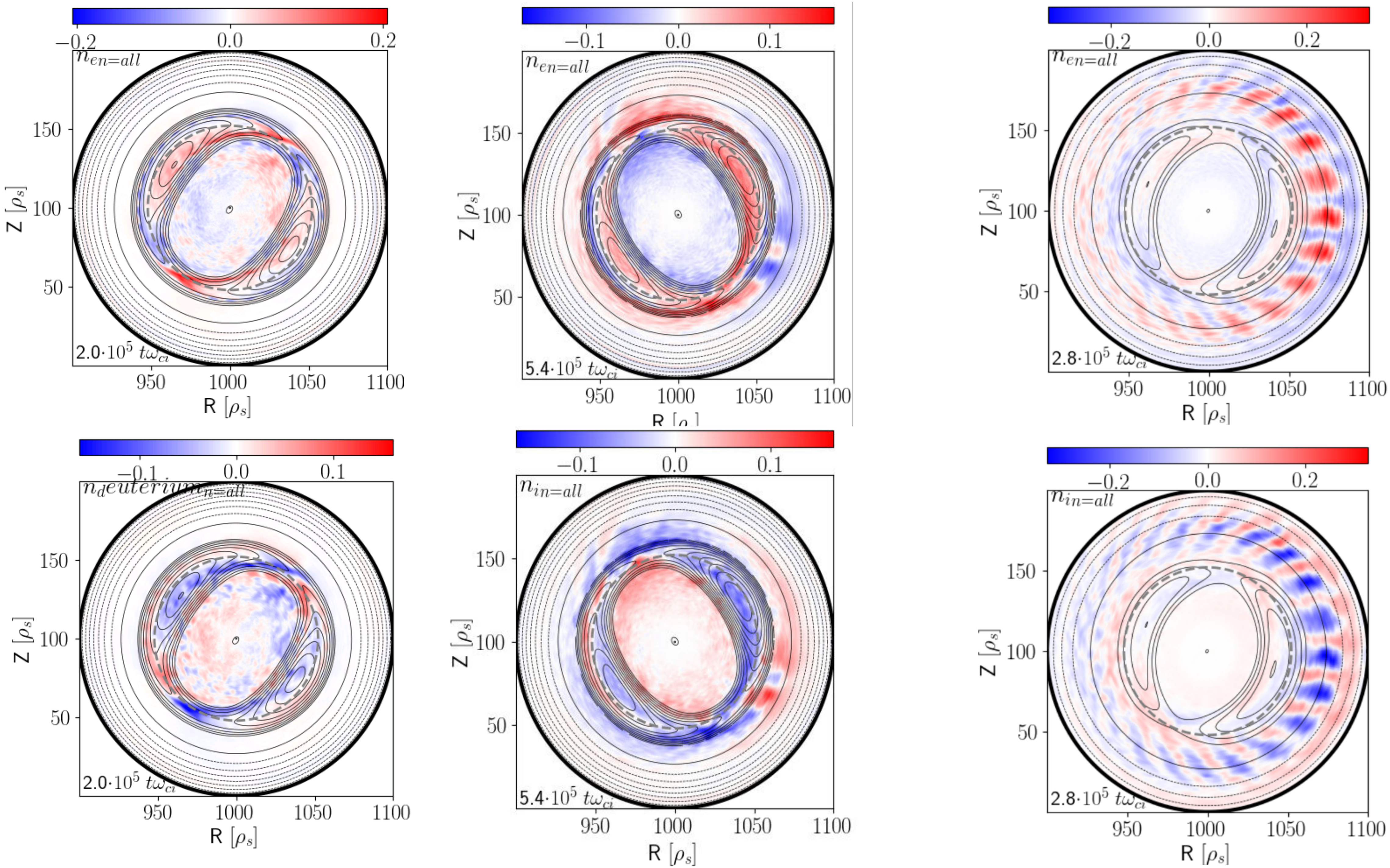
$\beta = 0.05\%$, $-R/L_T = 6$ potentials poloidal cuts

ϕ

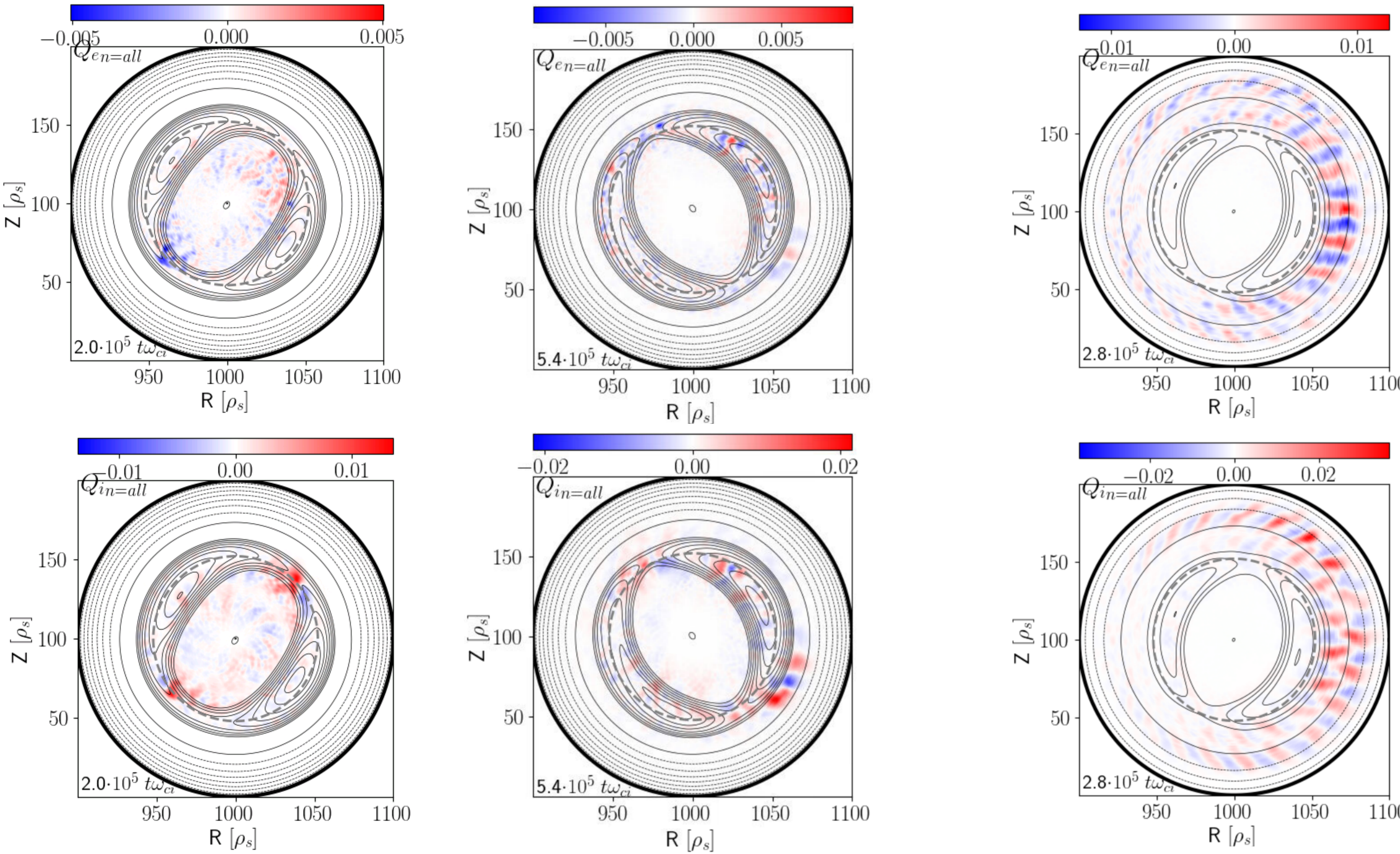
$A_{||}$



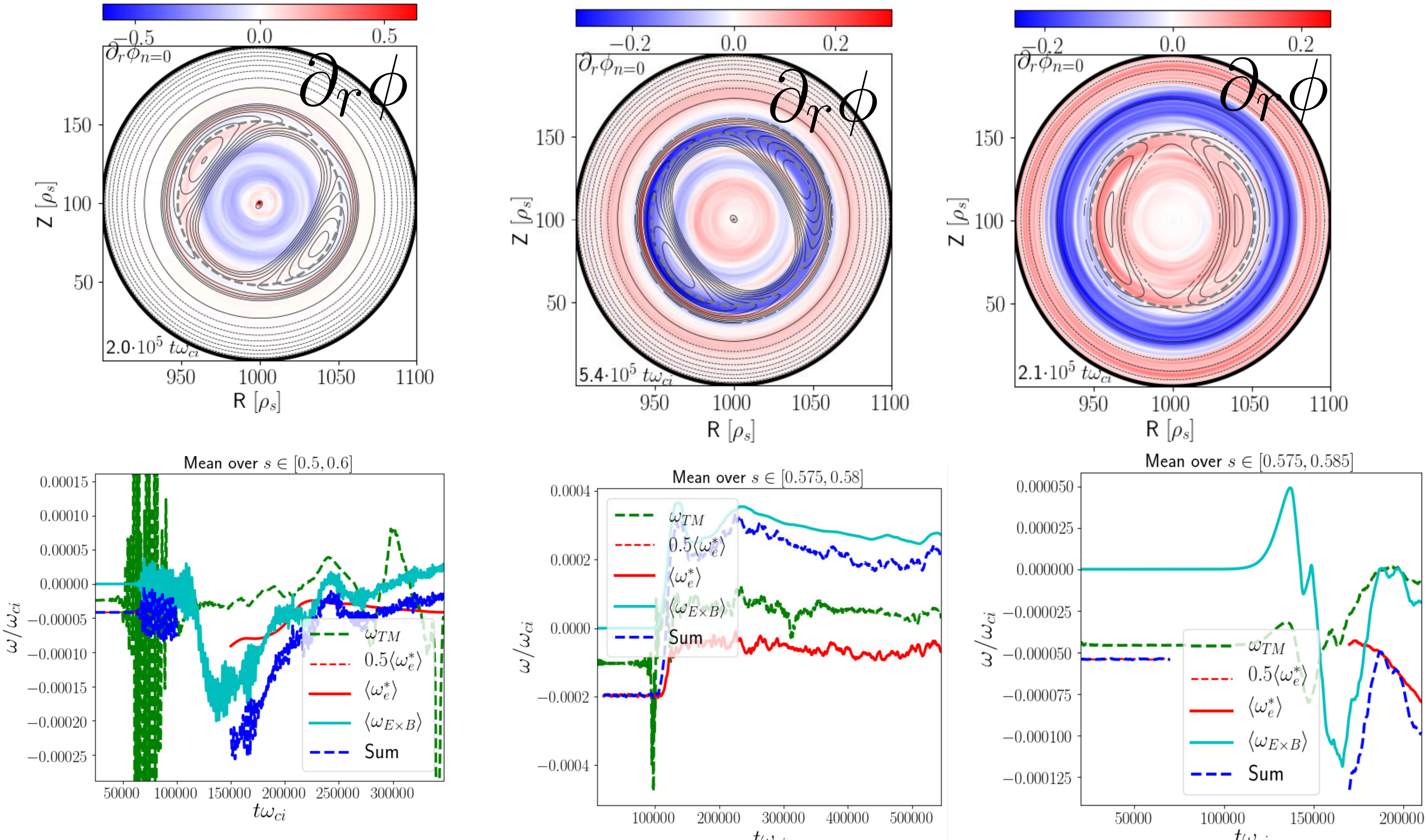
$\beta = 0.05\%$, $-R/L_T = 6$, Perturbed densities



$\beta = 0.05\%$, $-R/L_T = 6$, Heat Fluxes

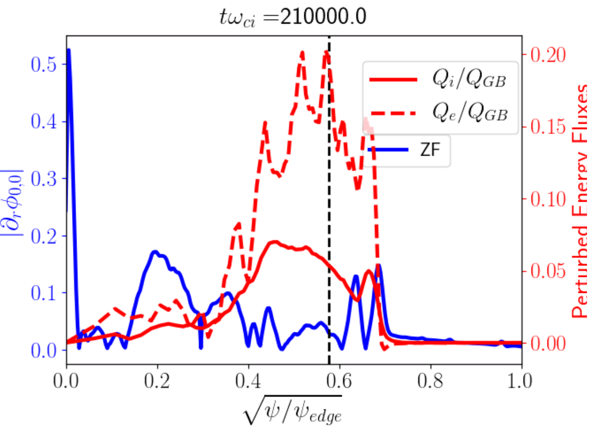


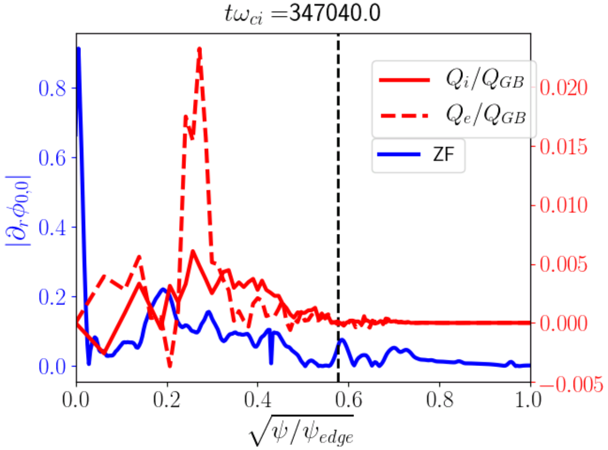
Zonal Flows and Large Island Rotation Frequency: $\langle V_{isl} \rangle \cong \langle E \times B \rangle$



Island increases the transport

r/a=0.3





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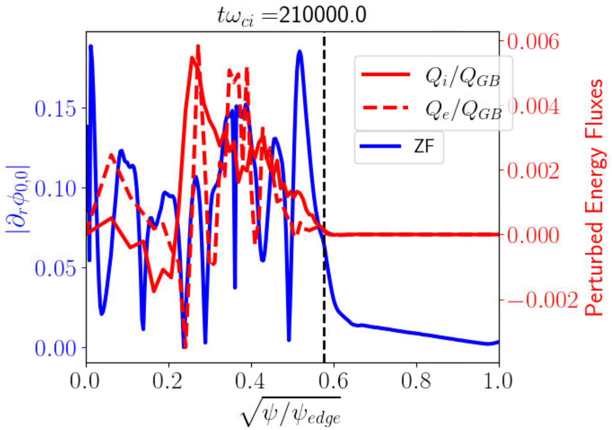
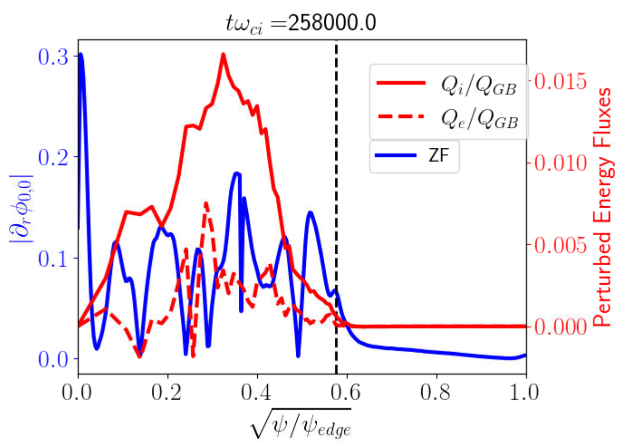
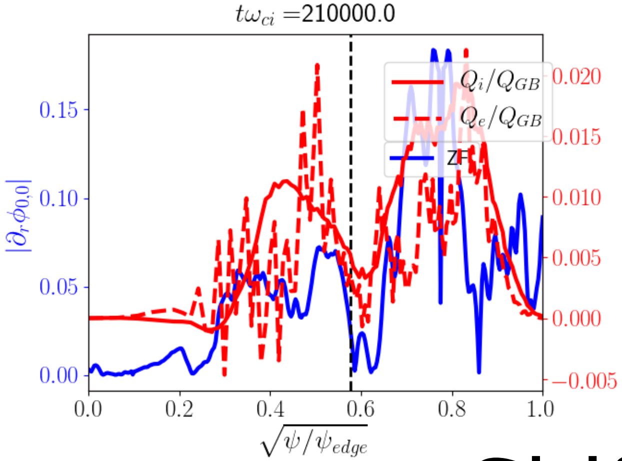
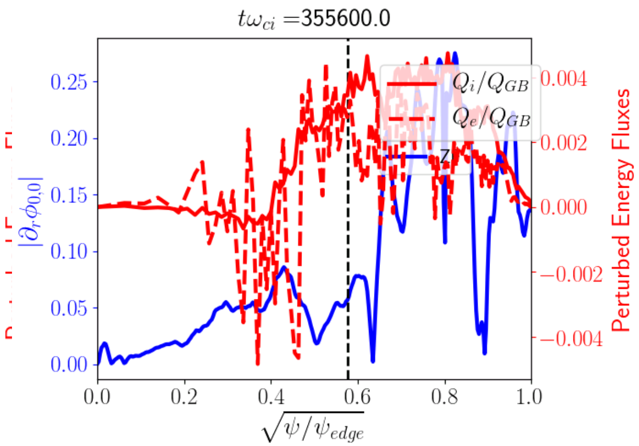
Unshifted





r/a=0.7





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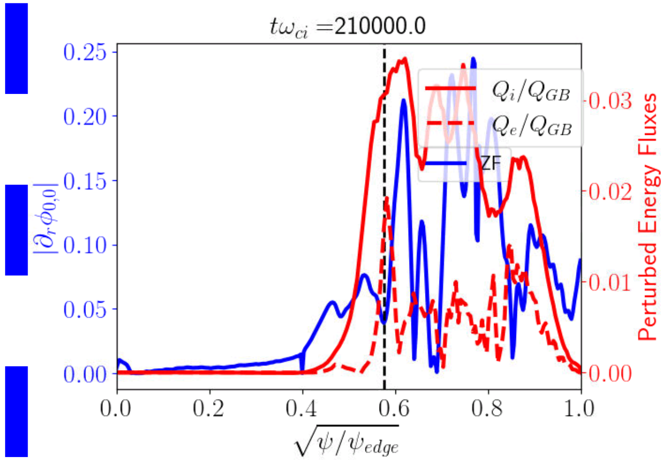
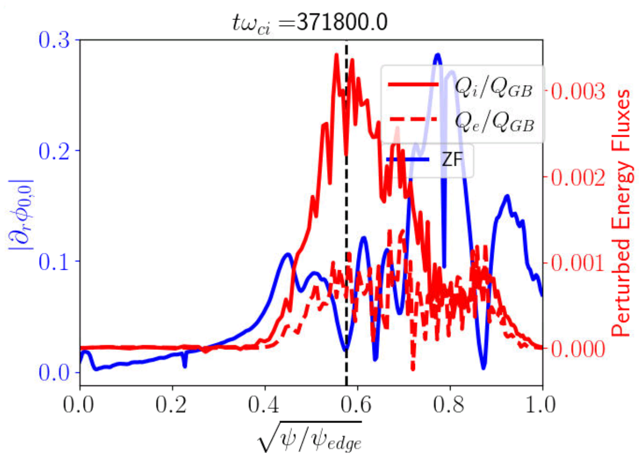
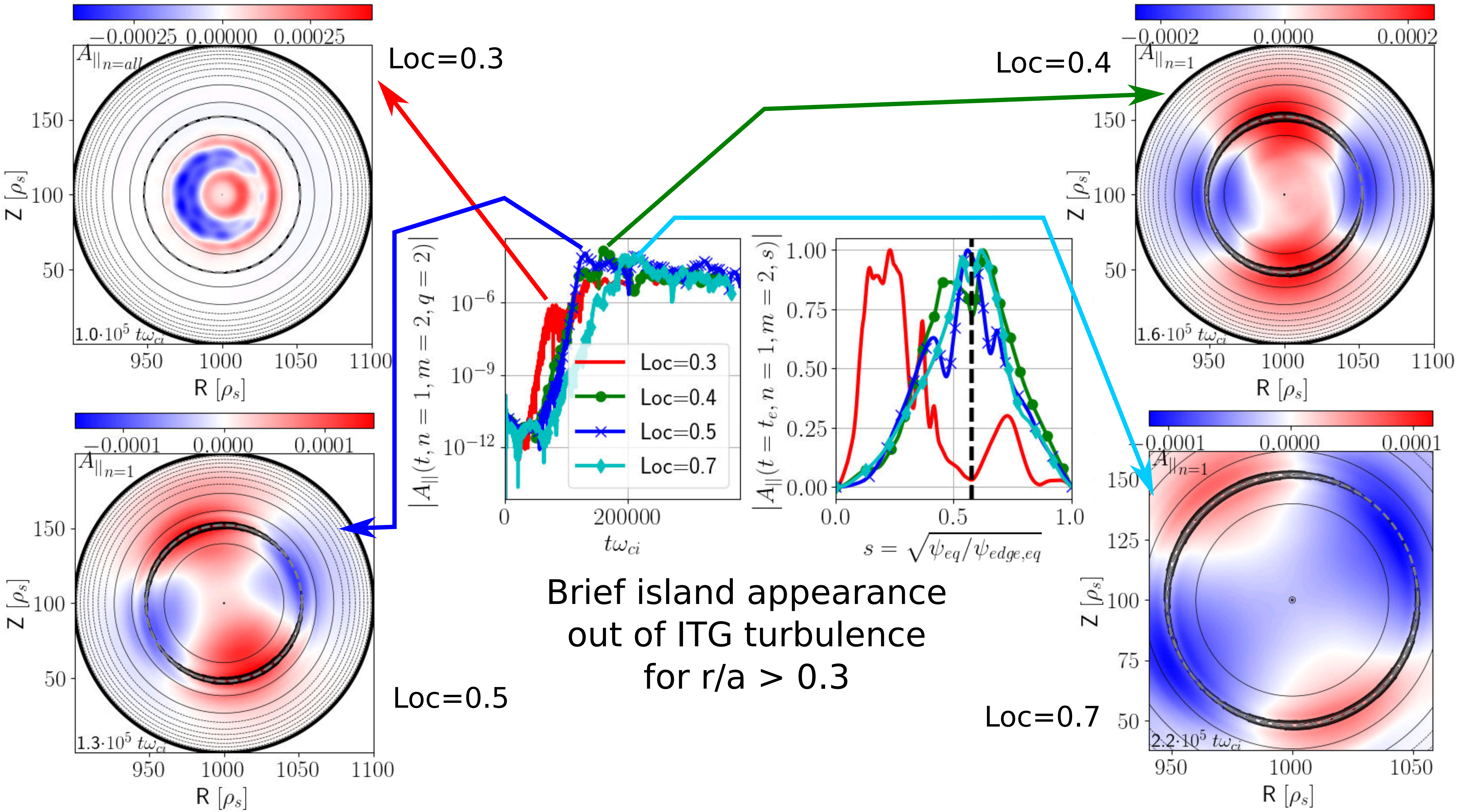
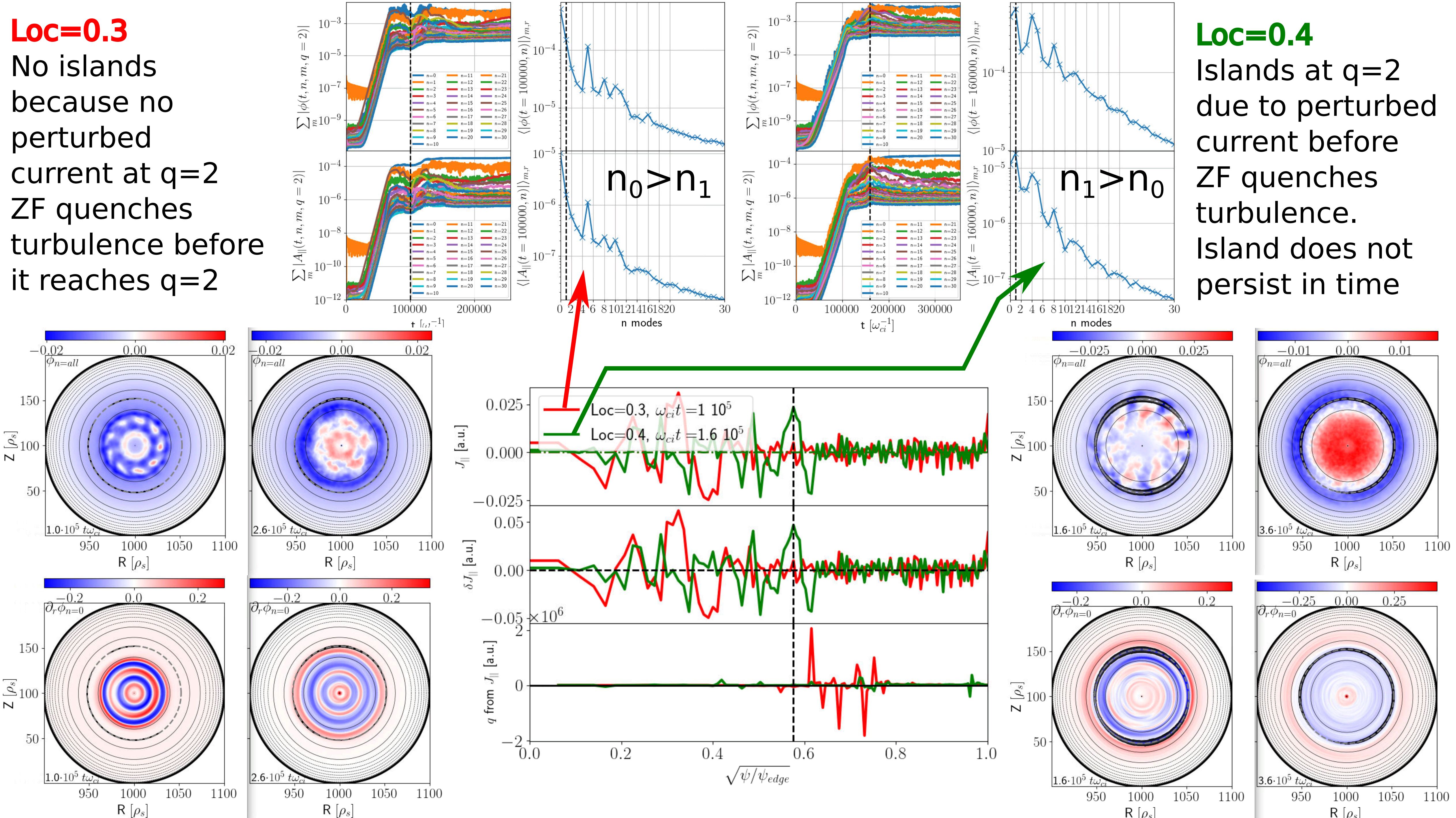






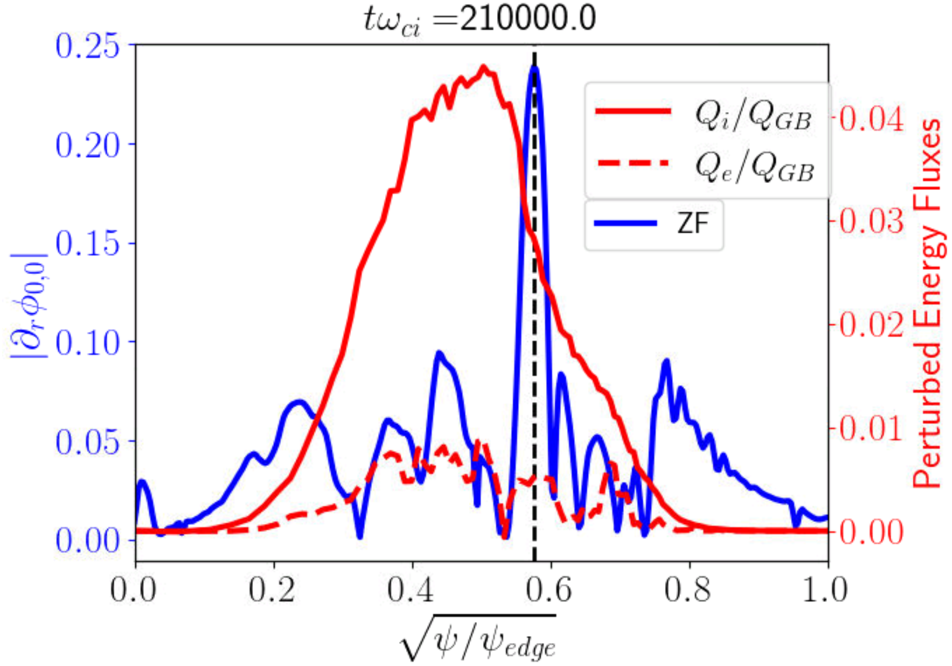
Brief island appearance out of ITG turbulence for r/a > 0.3

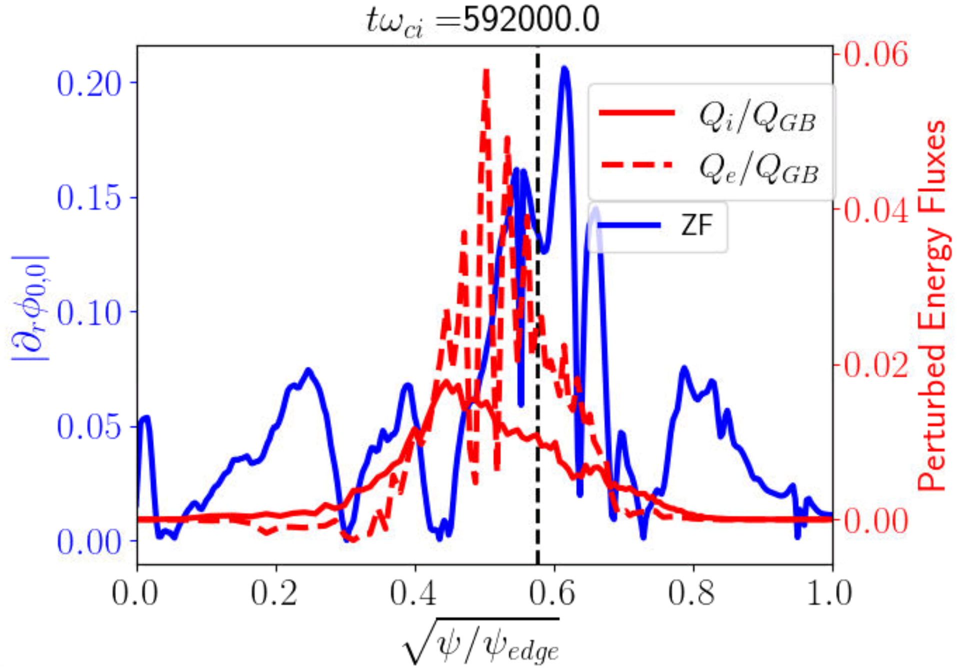
Loc=0.3
No islands because no perturbed current at q=2 ZF quenches turbulence before it reaches q=2



Loc=0.4
Islands at q=2 due to perturbed current before ZF quenches turbulence. Island does not persist in time

Shifted





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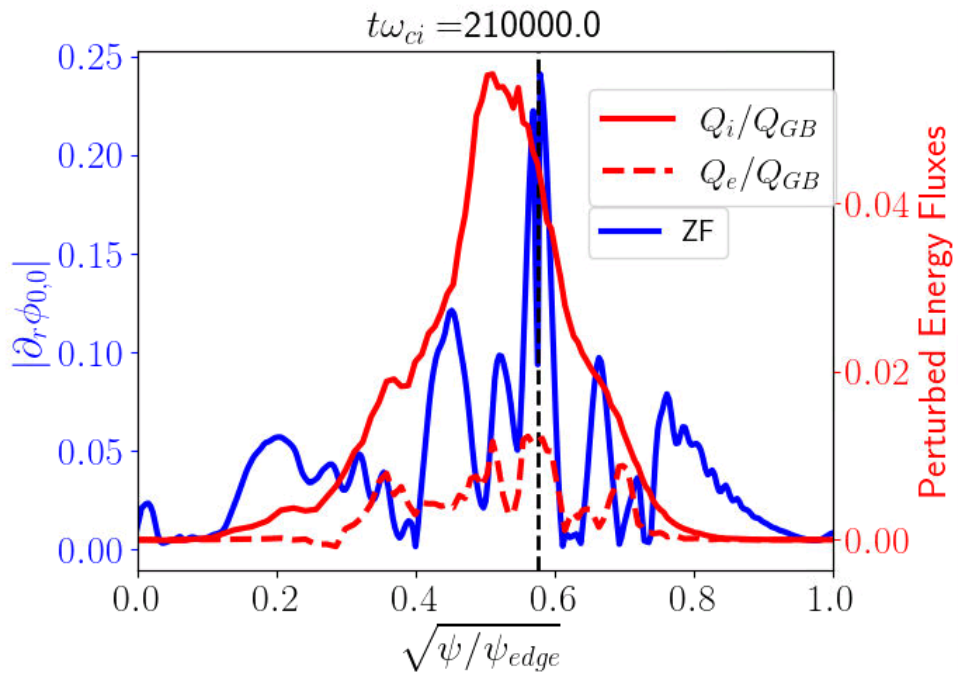

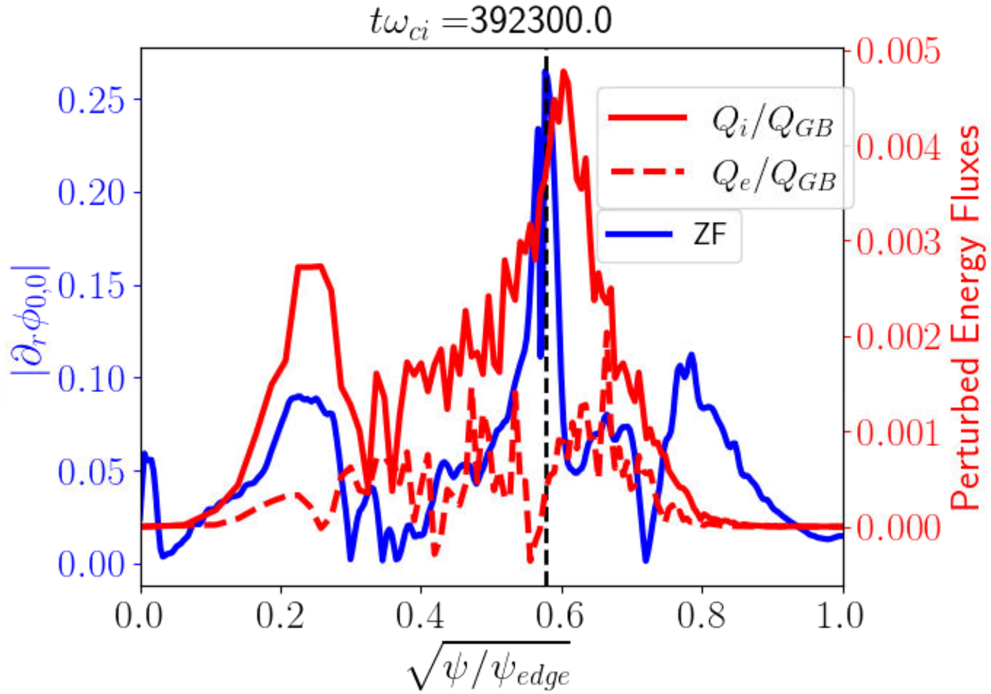

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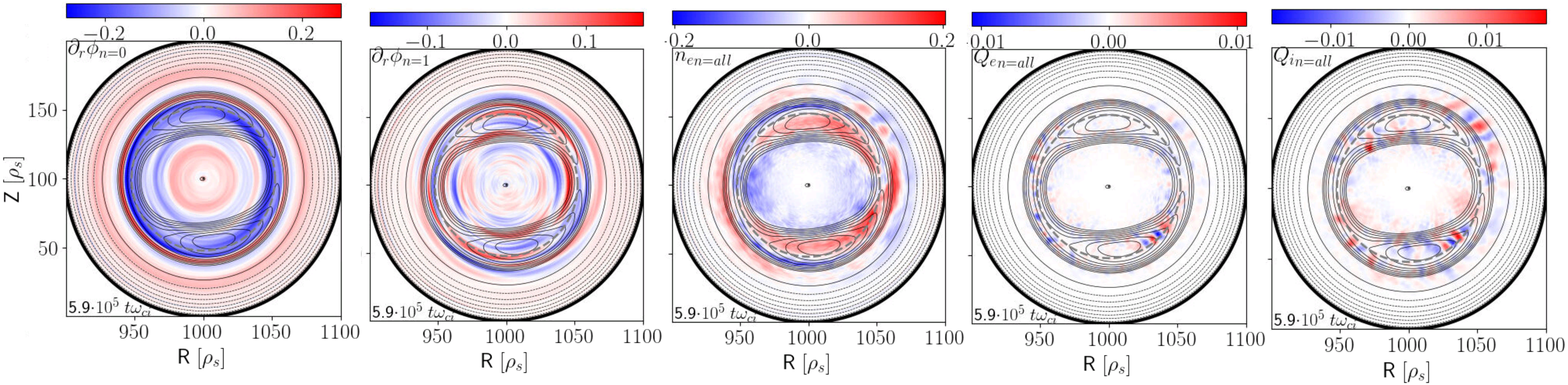

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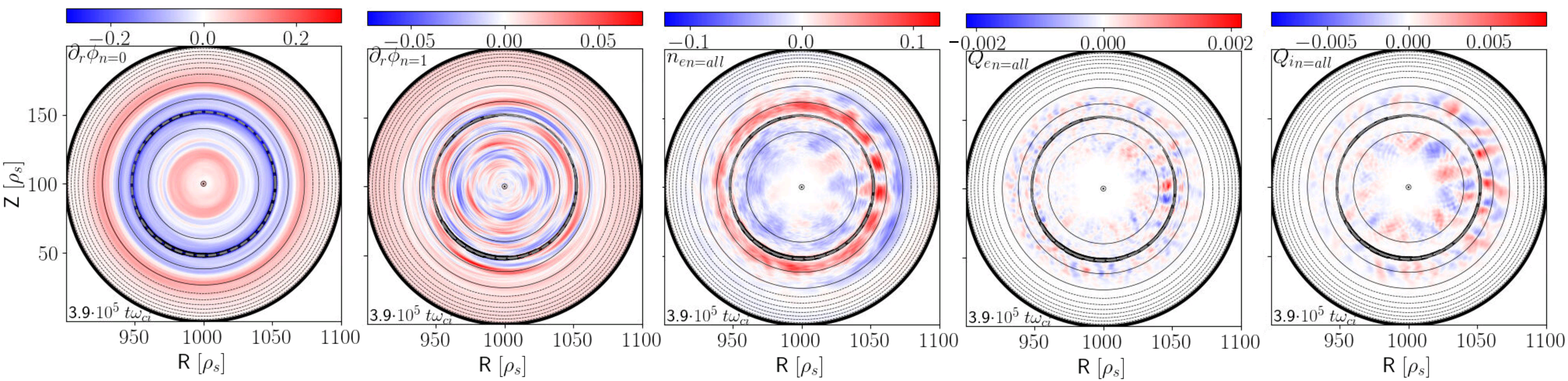

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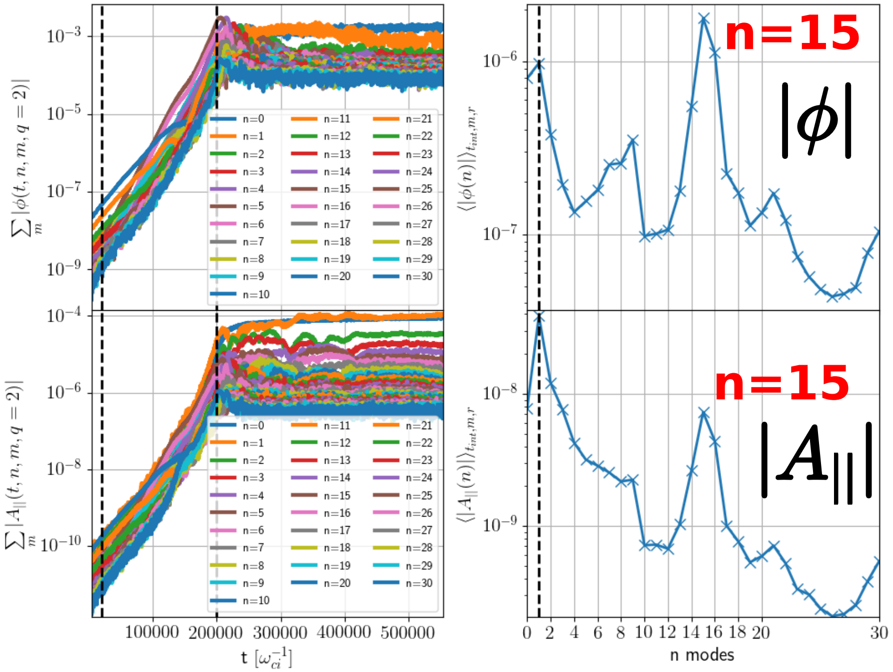
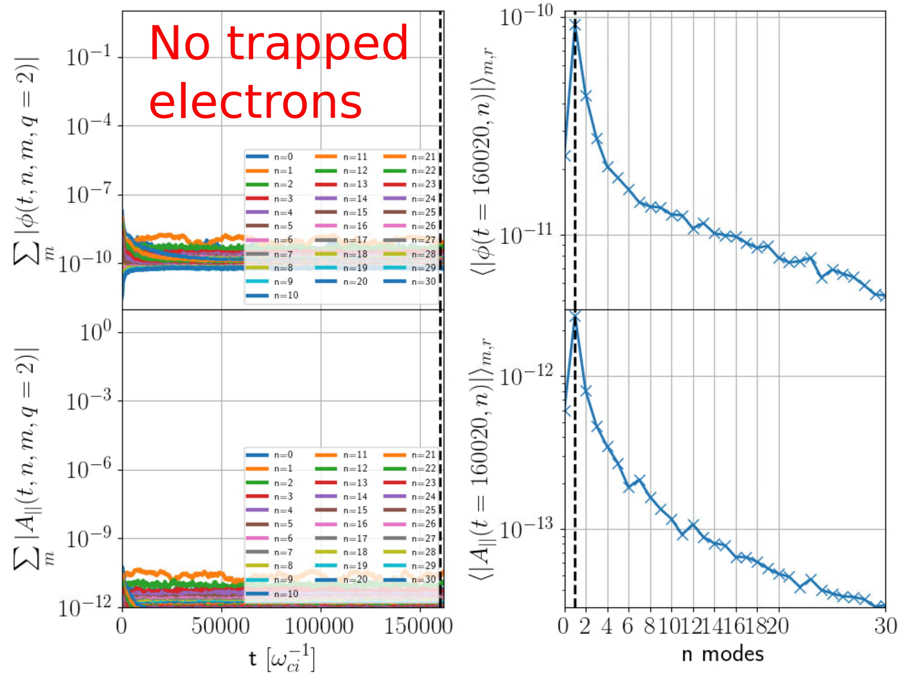
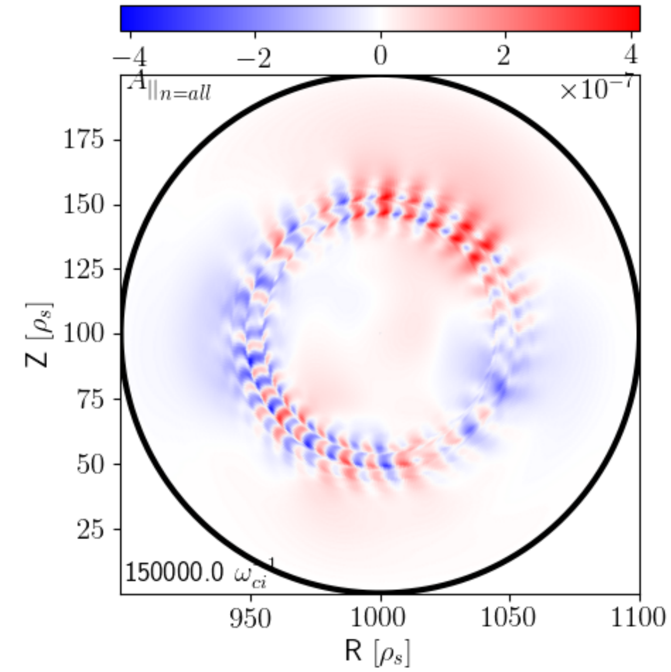
Electron-Driven Turbulence with Trapped elec: persistent island

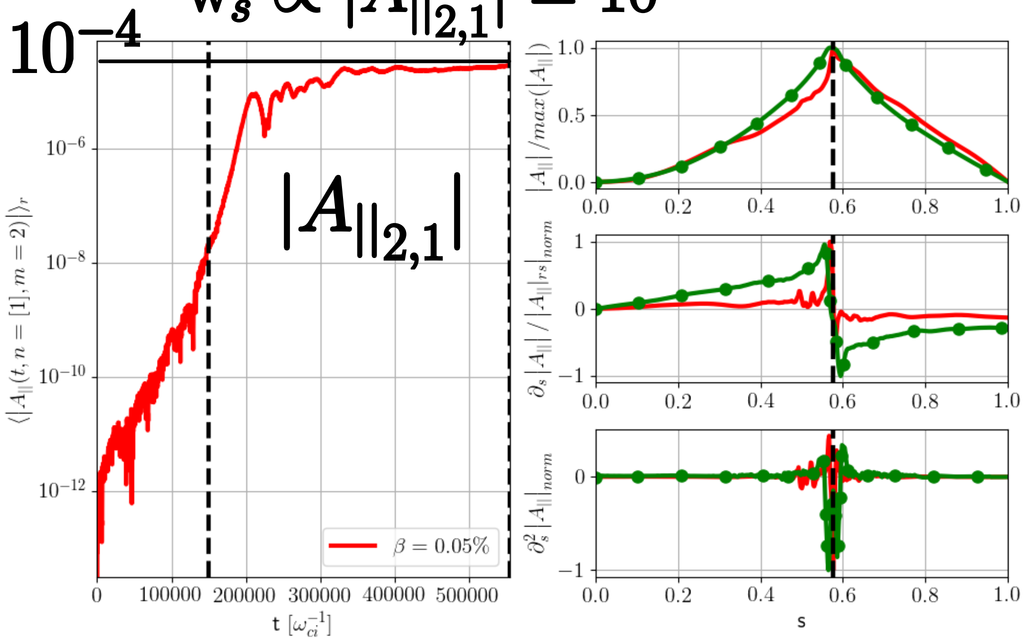
$R_0\nabla T_e/T_e = 6,\ R_0\nabla T_i/T_i = 0,\ R_0\nabla n/n = 1,\ \beta = 0.05\%$

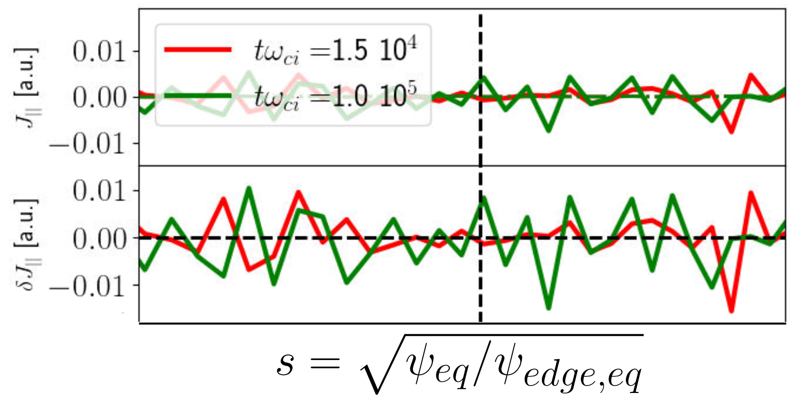




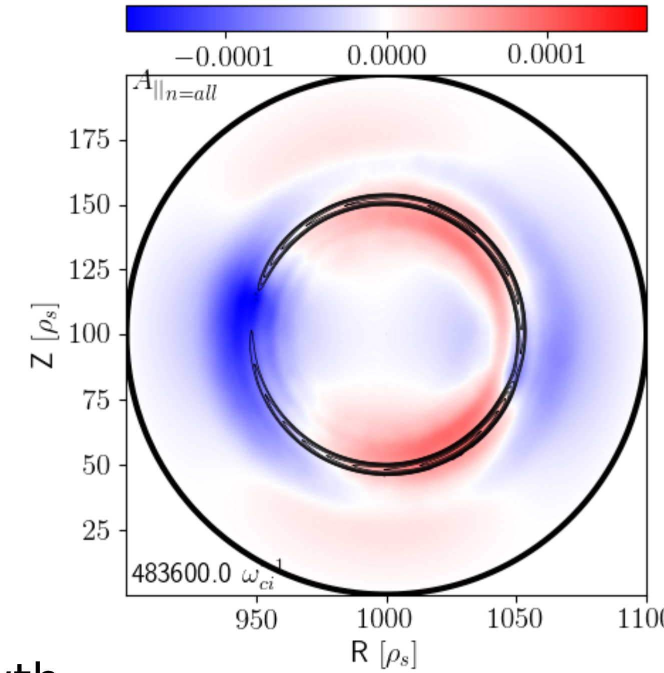


$w_s^2 \propto |A_{||2,1}| \cong 10^{-4}$





- Pertubed current at q=2 destabilises the island.
- Artificially removing the mirror force for the electrons: no growth



Conclusions

- ITG turbulence enhance the growth, quasi-steady state appears earlier
- Island second growth because of perturbed current
- Island enhances the turbulent transport when the gradients are localised away from rational surface
- Island can act a quasi-internal transport barrier because of flows produced at its separatrix
- An island can be produced from turbulence because of a perturbed current, but sustained for electron driven turbulence only
- The role of trapped electrons seems crucial in collisionless limit to generate an island out of turbulence from a stable tearing mode.