Global EM turbulence in W7-X using EUTERPE

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Motivation

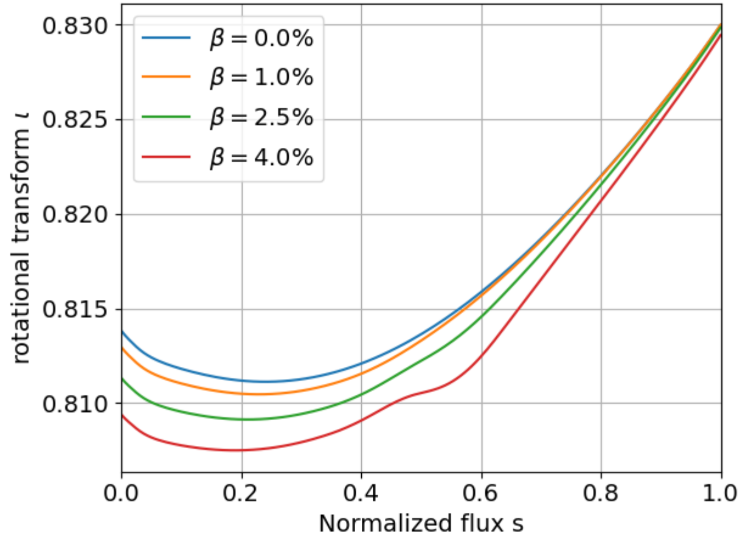
- W7-X is shown to be turbulence dominated due to neoclassical optimization
- High performance is achieved at higher β-values
- Small and large/global scales interact and can generally not be separated

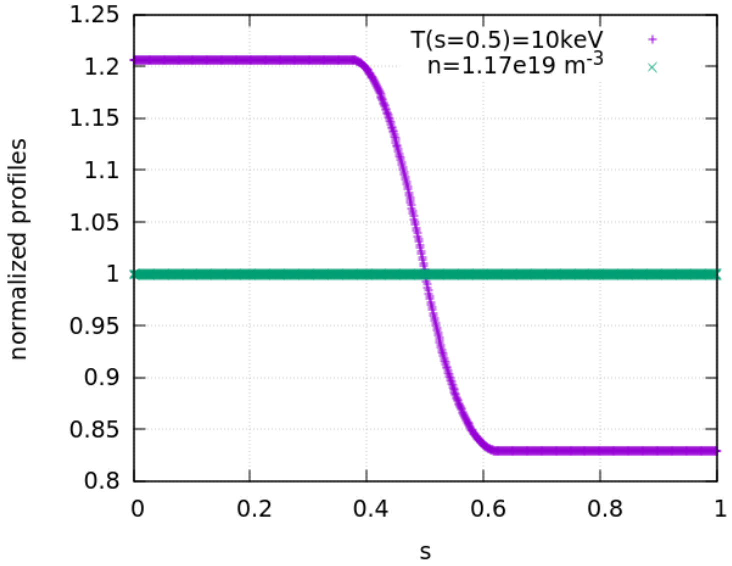
- Open question of interplay between turbulence, ZFs and mode activity in EM dominated regimes

- Here: a series of global NL EM simulations are performed to investigate turbulence in W7-X

Setup of simulations

- **The W7-X UFM configuration is investigated:**
  - Low shear / flat iota
  - Very high mirror ratio of 28.5%
  - Mercier-unstable (strong linear drive)
- **Profiles**
  - $T_e = T_i$, flat density,
  - Finite $\nabla T_{e,i}$, $a_0 \nabla T / T = -4.2$
  - β is scaled via flat density to $\langle\beta\rangle = 1.0\%, 2.59\%, 4.16\%$
- **The plasma profiles and VMEC equilibria are consistent.**



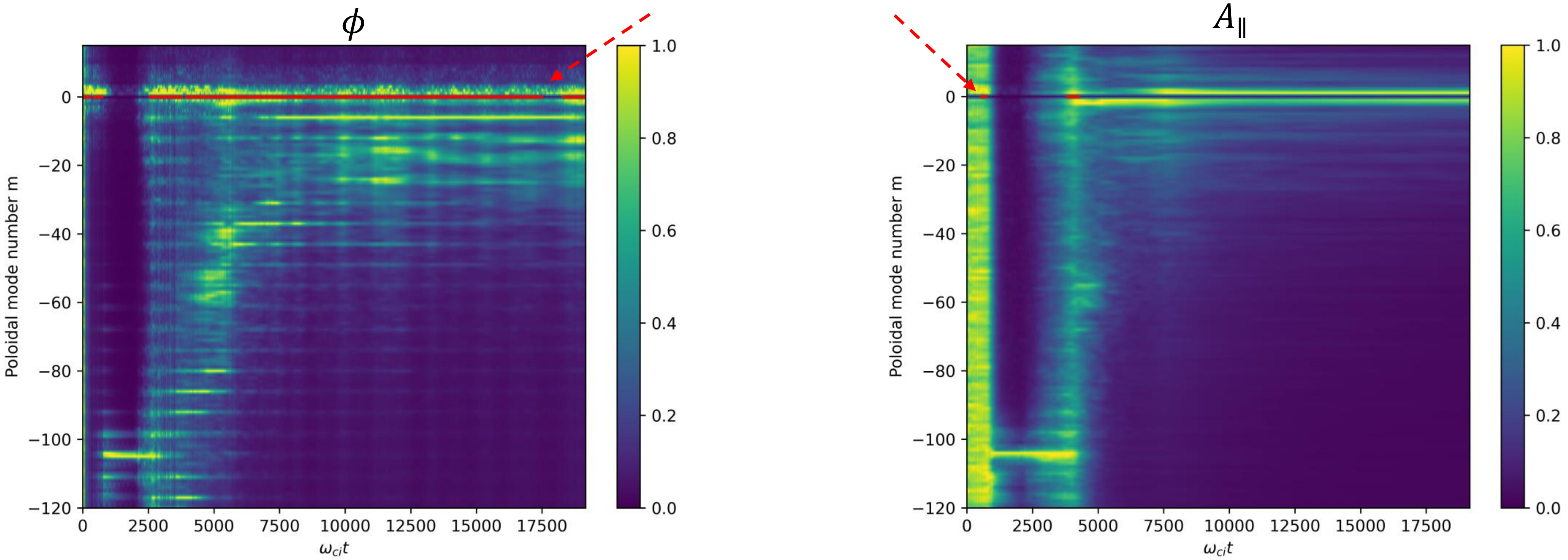


Numerical information

- **We use the global δf PIC-code EUTERPE.**
  - Simulations are fully kinetic in the electromagnetic regimes $\boldsymbol{\delta} A_{\parallel} \neq 0$ and $\delta B_{\parallel} \neq 0$.
  - Gyrokinetic ions, drift kinetic electrons
  - Grid for fields $N_s \times N_\theta \times N_\varphi = 128 \times 512 \times 128$
  - Particle markers $N_e = 1.25 * 10^9$, $N_i = 0.75 * 10^9$
  - Simulation domain is restricted to $s = [0.2,\ \ 1.0]$
  - Mass ratio $m_i/m_e = 200$
- **Cost per simulation:**
  - About $1.5 - 2 * 10^6$ CPUh => 6 million CPUh
  - For real electrons about x3 higher due to time step adjustment
- **Simulations were executed on the Viper (MPG) and MareNostrum4+5 (BSC) supercomputers**

Spectral activity - $\beta = 1\%$

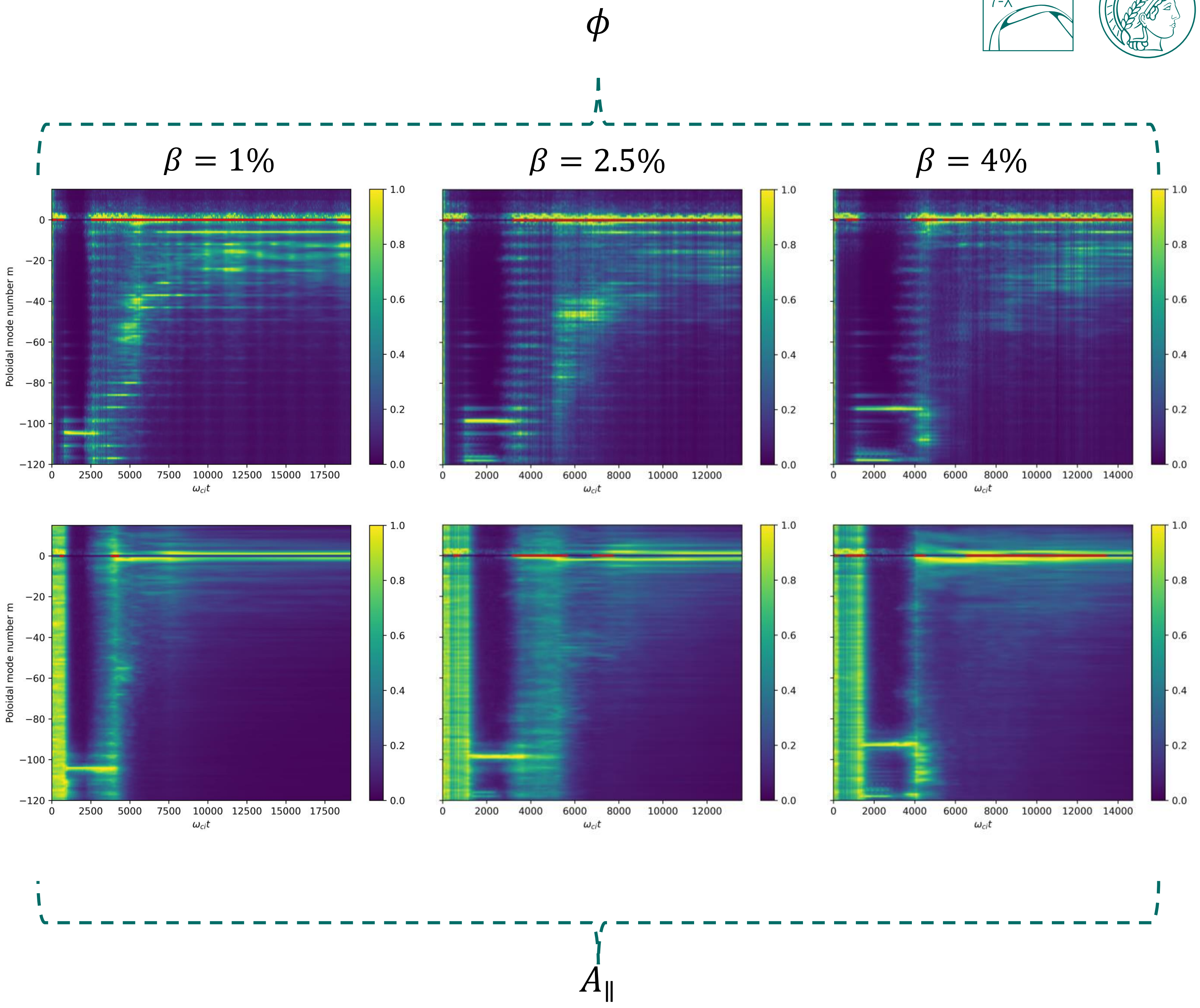
Red line ZF is maximum



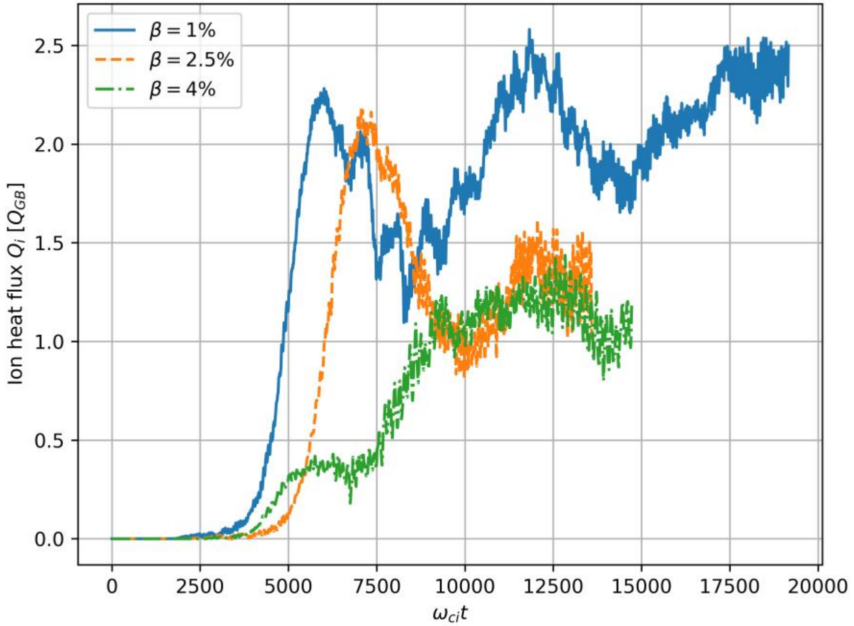
- **Normalized spectral power shows evolution of activity in time:**
  - ZF stabilizes initial electron driven mode (m ~ 120 – 100, $k_\perp \rho_i \approx 1.4$)
  - All scales become active and ZF stabilizes intermediate ITG (m ~ 40 – 60, $k_\perp \rho_i \approx 0.65$)
  - Broad large scale activity follows
  - $A_\parallel$ generally follows ϕ, but jumps to very large scales as electron mode is stabilized

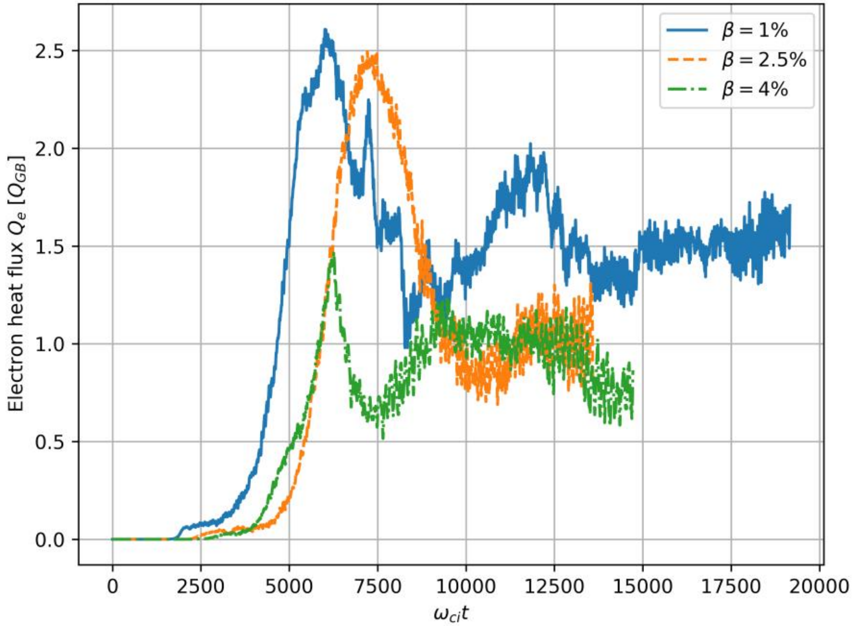
Spectral activity – all β

- **1% and 2.5% similar (elec. Mode + ITG => both ZF-stabilized)**
- **At 4% initially elec. Mode, then yet unidentified mode active in $A_{\parallel}$ and ϕ**
- **Late stages show broad activity at large scales and only weak activity at small scales**



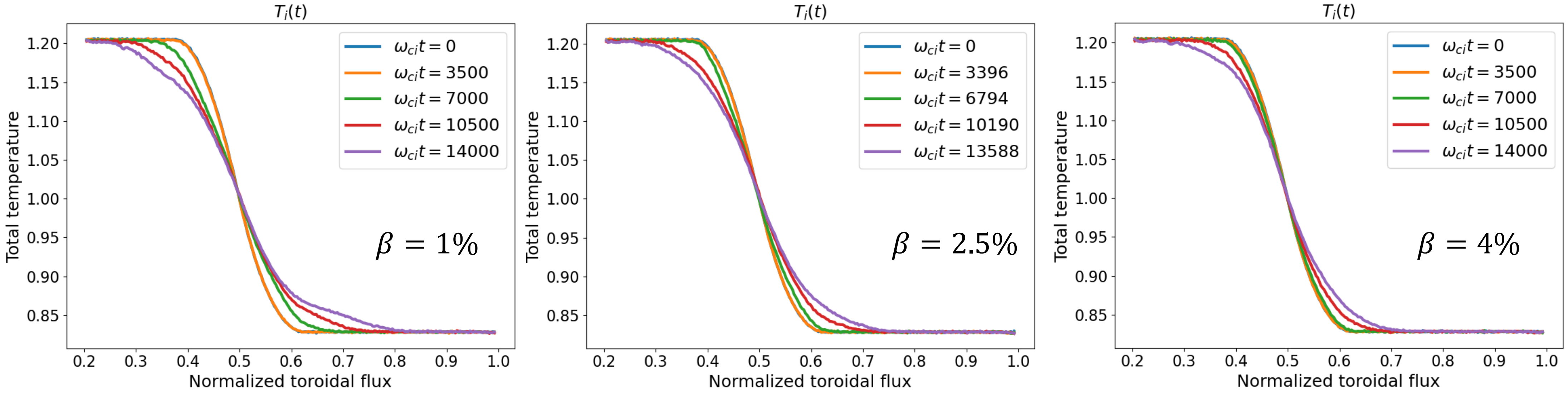
Heat fluxes



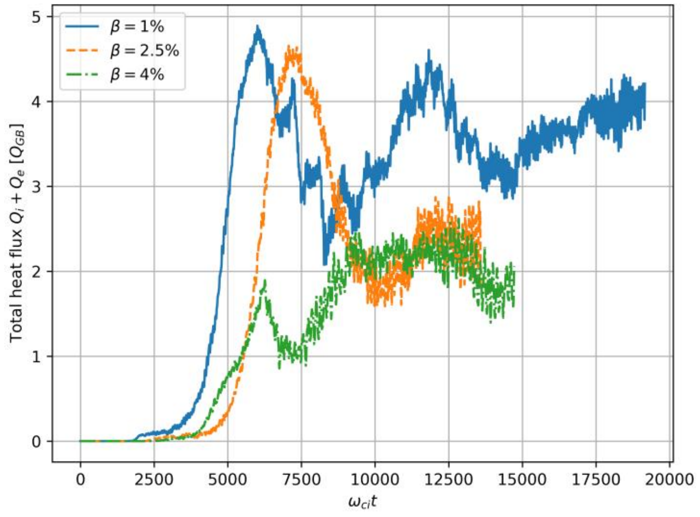


- **Steady state fluxes obtained without simulations crashing.**
  - Initial flux peak driven by ITG-mode. At $\beta = 4\%$ strong Q_e by small scale mode.
  - During linear phase $Q_e > Q_i$, but during late NL-phase $Q_i > Q_e$ (for $\beta = 1\%$)
  - For $\beta = 2.5\%$ and 4% $Q_e \approx Q_i$ during NL-Phase, within statistical uncertainty
- **No catastrophic increase of fluxes observed due to EM-activity.**
  - **Instead: Steady state fluxes reduce with β.**

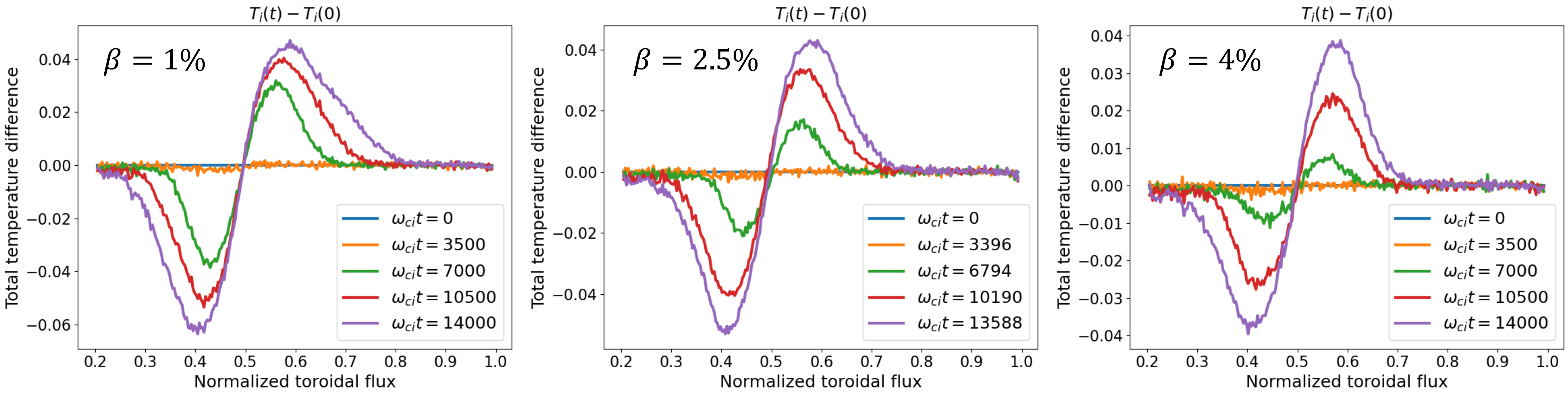
Temperature profile evolution



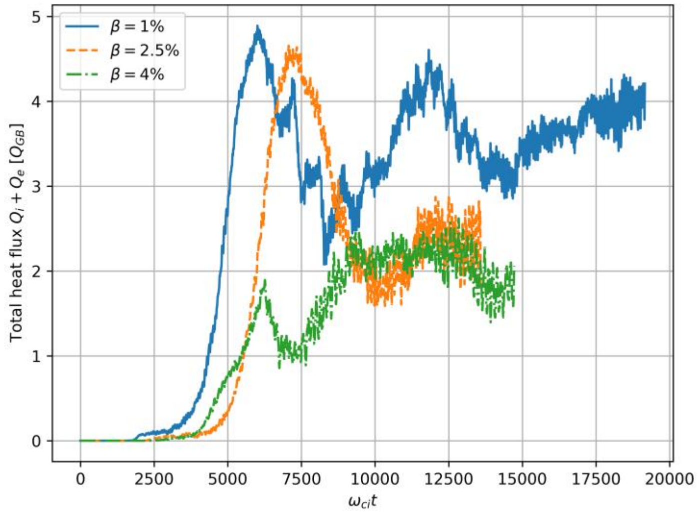
- **Strongest temperature relaxation in $\beta = 1\%$-case**
  - Changed profile becomes increasingly linear in late stages at s=0.6-0.8. Deeper meaning?



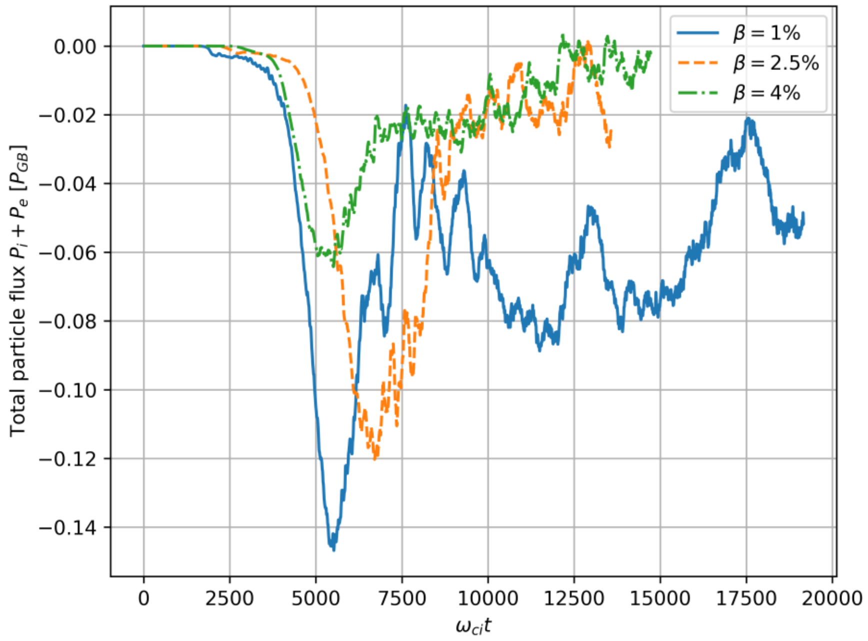
Temperature profile evolution

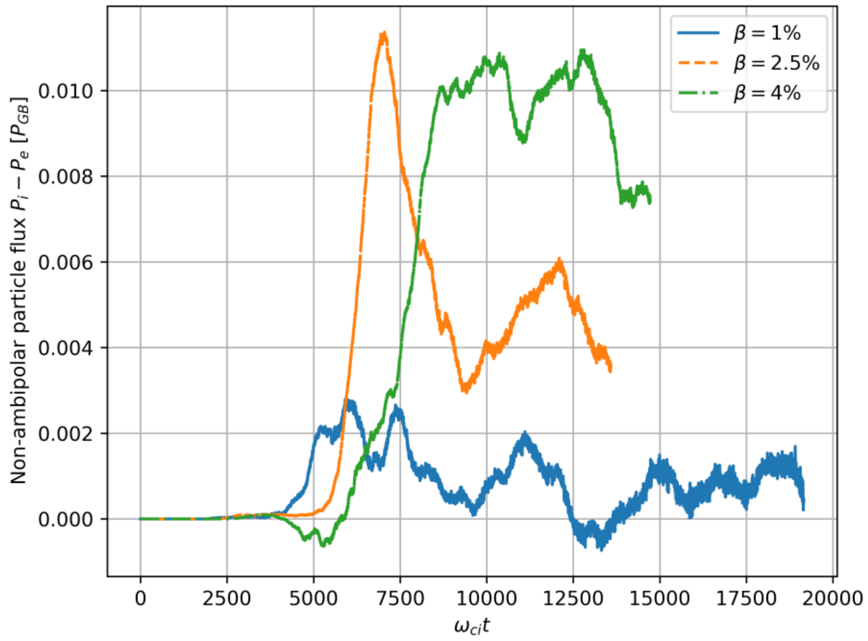


- **Strongest temperature relaxation in $\beta = 1\%$-case**
  - Changed profile becomes increasingly linear in late stages at s=0.6-0.8. Deeper meaning?
- **Temperature at steepest gradient (s=0.5) unchanged**
- **Turbulent region becomes wider as profile flattens and gradient-region expands**



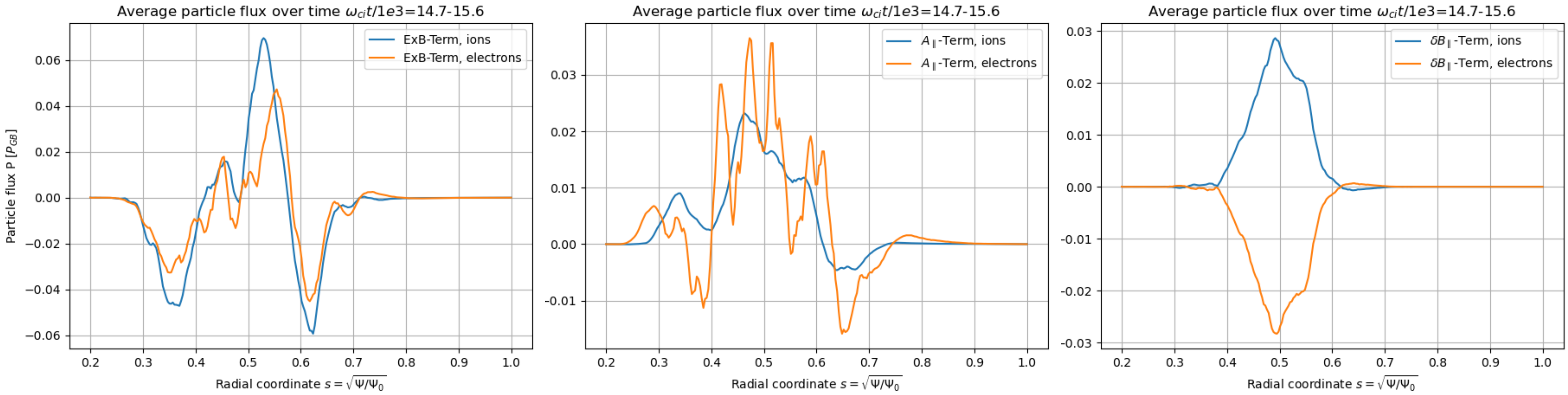
Particle Fluxes





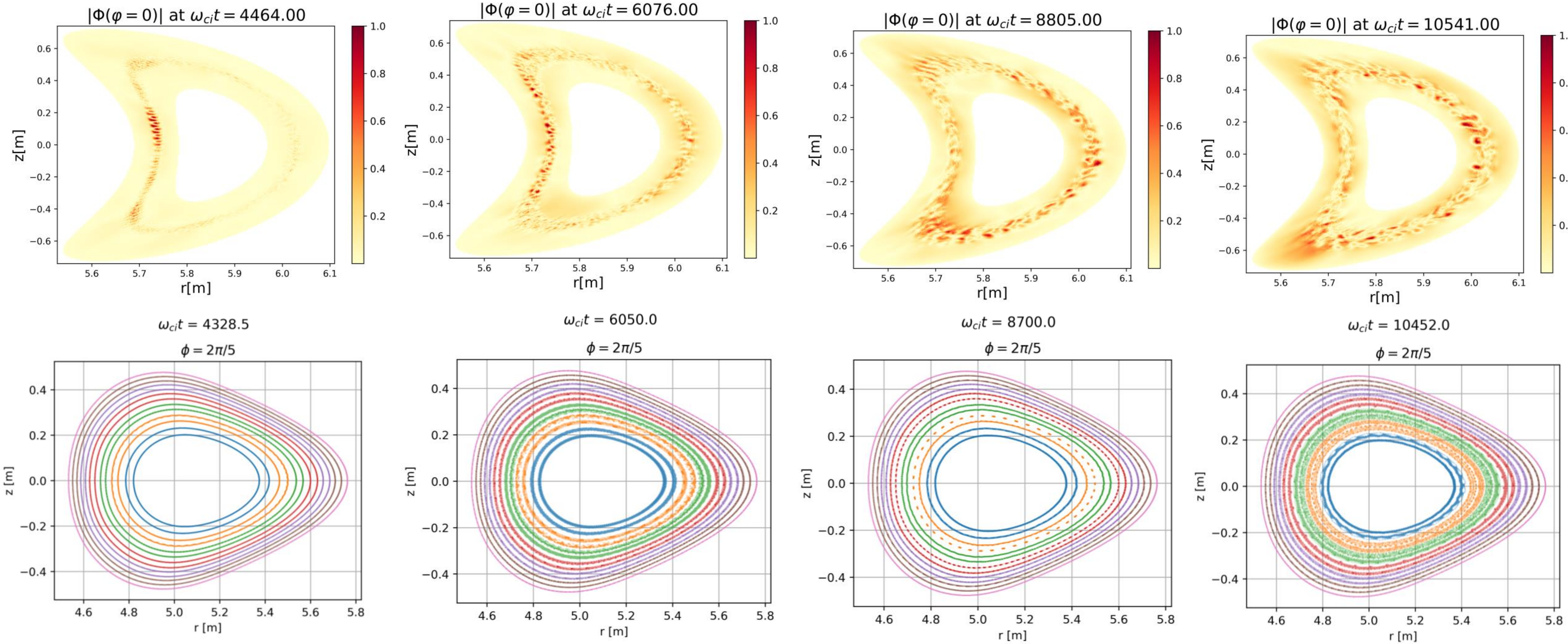
- **Particle fluxes show pinch**
  - Buildup of density gradient
  - Pinch decreases in strength with increasing β
- **Small non-ambipolar particle flux observed => increases with *β***

Non-ambipolar particle fluxes - $\beta = 4\%$



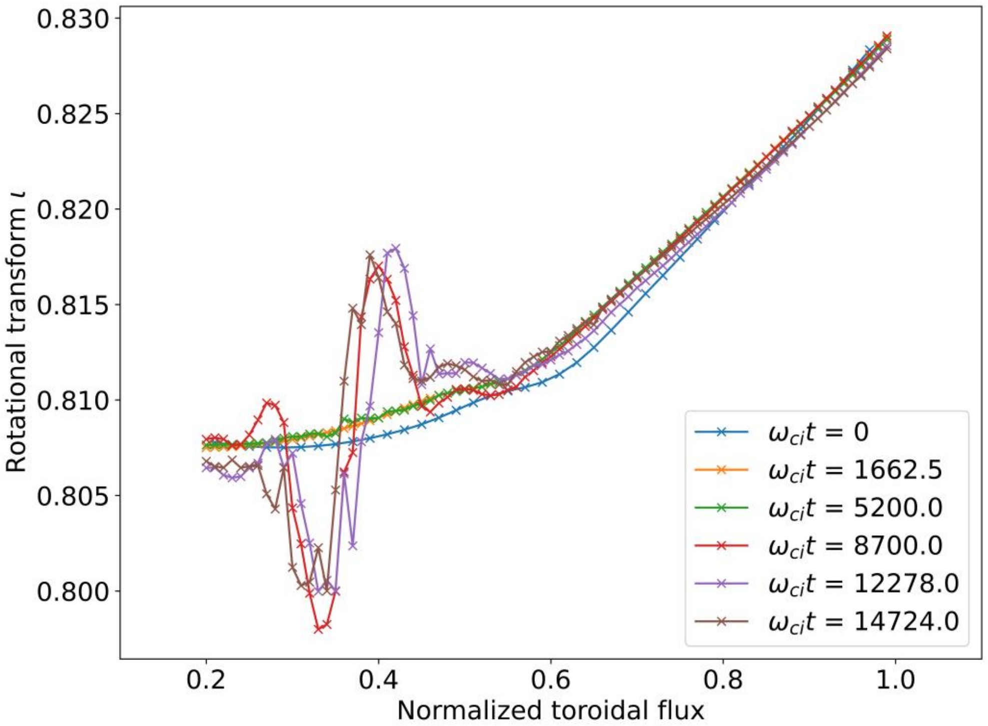
- **Continuation of sim. to split particle fluxes into physics terms: ExB, $A_\parallel$ and $\delta B_\parallel$**
  - Slight difference in ExB-term => almost the same, as expected
  - Flutter term shows strong peaks by electrons => Electrons react more to flutter because $v_{th,e} \gg v_{th,i}$ and drift-kinetic treatment
  - $\delta B_\parallel$-flux: $P_{\delta B_\parallel,i} \approx -P_{\delta B_\parallel,e}$ since charge in drift-term: $\frac{\mu}{qB}\vec{b} \times \nabla \delta B_\parallel$ and LW-approximation

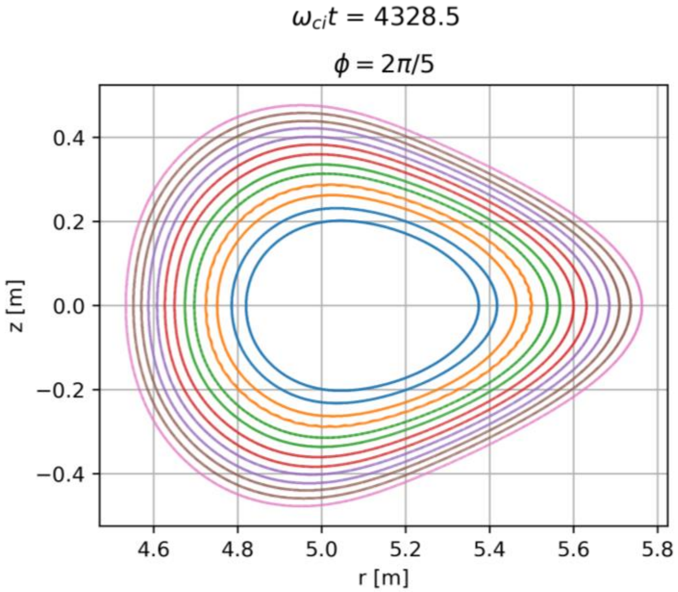
Ergodization of flux surfaces and reconnection

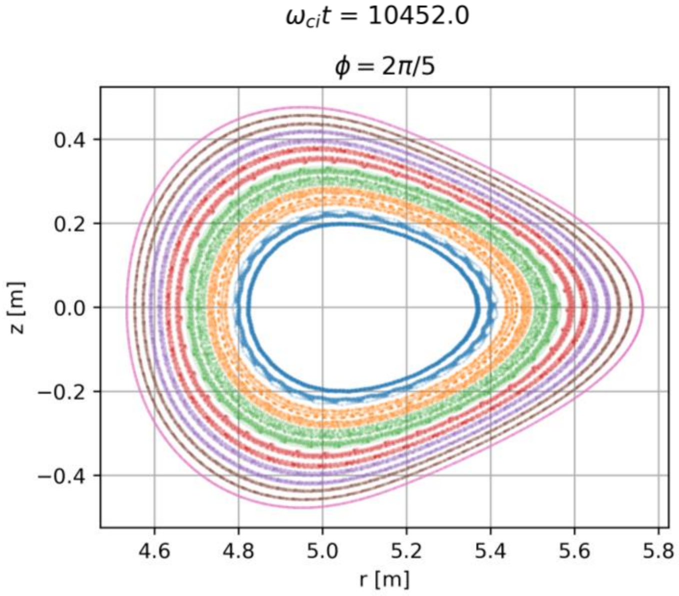


- **Linear mode develops into turbulence and spreads throughout plasma**
- **Turbulence causes partial reconnection and destruction of flux surfaces**

Turbulence perturbed rotational transform



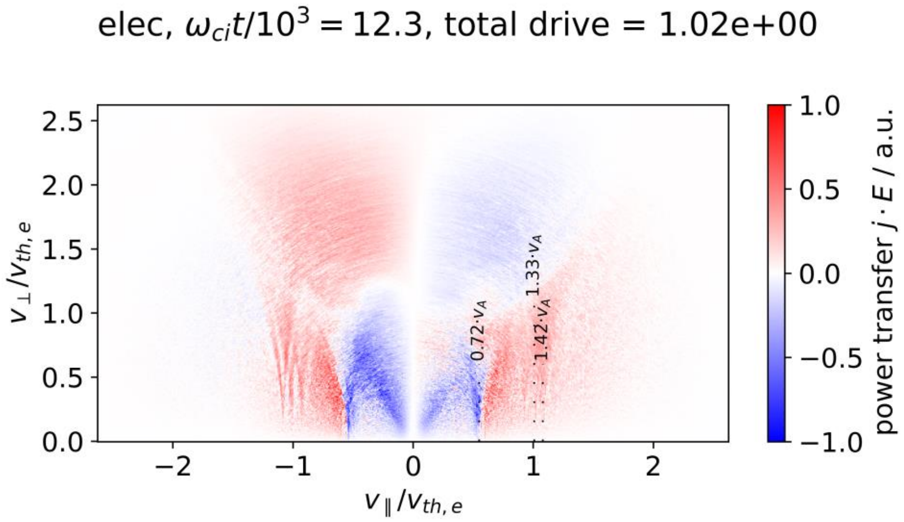




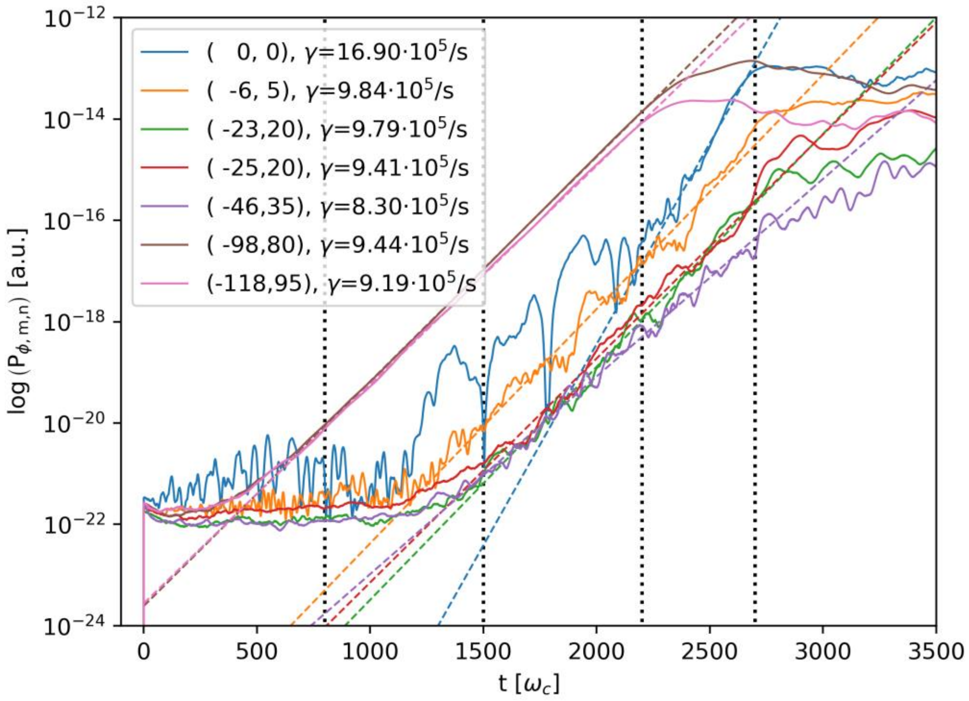
- **Strong perturbation of rotational transform due to turbulence**
- **Optimization of magnetic field geometry partially lost under turbulence**

Extras

- **Phase-Space energy transfer plots**
  - Electron drive in linear phase and ion drive in NL-phase
  - Show $\boldsymbol{v}_{\parallel}$-Resonances: potential Alfvénic-activity



- **Growth rate cascades?**
  - Indications for beat-driven ZFs: $\boldsymbol{\gamma_{ZF} = 2\gamma_{instability}}$
  - Difficult to find EXACT matching (m,n) and γ
  - How precisely do these have to match?
  - Rather using ϕ or $A_{\parallel}$ for this?



Open questions

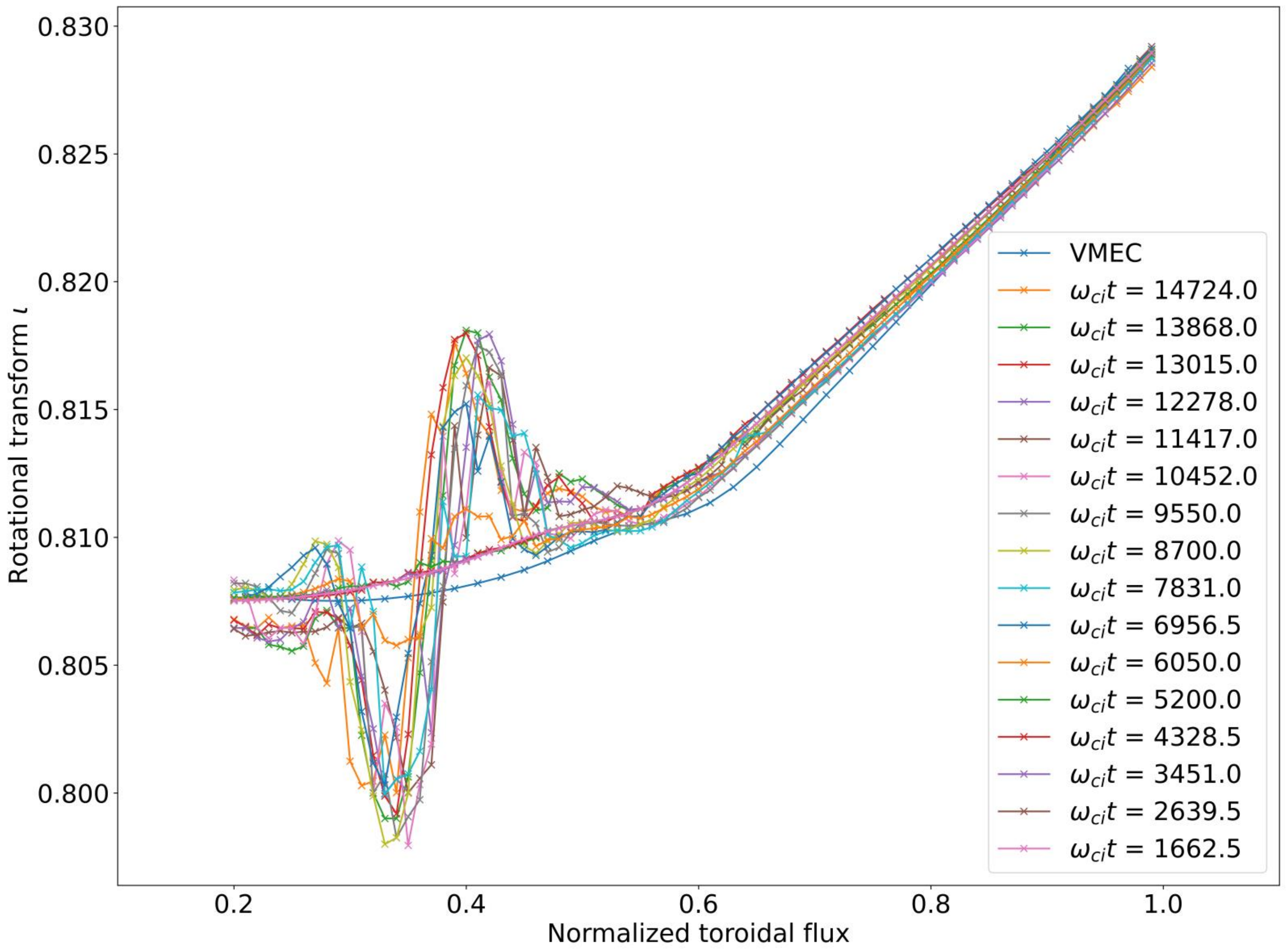
- Initial (and linearly dominant) small scale instability is not active in late stages but does drive a ZF which might regulate turbulence. Is that important to simulate? What happens if that instability is left out and the ZF is weaker?
- Does the non-ambipolar particle flux create a radial electric field (-> ZF) that sheares turbulence apart, thus causing stabilization of heat fluxes? Test by deactivating dBpar?
- $\rho^* = \rho/a_0$-dependence of non-ambipolar particle flux?
- Flux surface ergodization, perturbed iota and particle flux terms at $\beta = 1\%$?
- Importance of Alfvénic activity? Worth investigating despite changed mass ratio?

Summary and conclusions

- **Global NL EM simulations have been performed for several $\langle\boldsymbol{\beta}\rangle$-values.**
  - No crashes of simulations due to unstable heat fluxes.
  - Reduction of heat fluxes up to $\langle\beta\rangle = 4.16\%$.
  - In fact: absence of strong increases in heat flux typical for MHD-modes or KBMs
- **Particle fluxes show pinch and even non-ambipolarities**
  - Pinch decreases with $\langle\beta\rangle$
  - Non-ambipolarities in all physics-terms but mainly driven by $\delta B_\parallel$-terms
- **Turbulence causes partial destruction + widening of flux surfaces and strong changes in the rotational transform profile**
  - Optimization of magnetic field geometry important but partially lost under turbulence
  - Reactor relevant configurations need to be resistant to turbulence
- **Indications for Alfvénic instabilities and beat-driven ZFs**

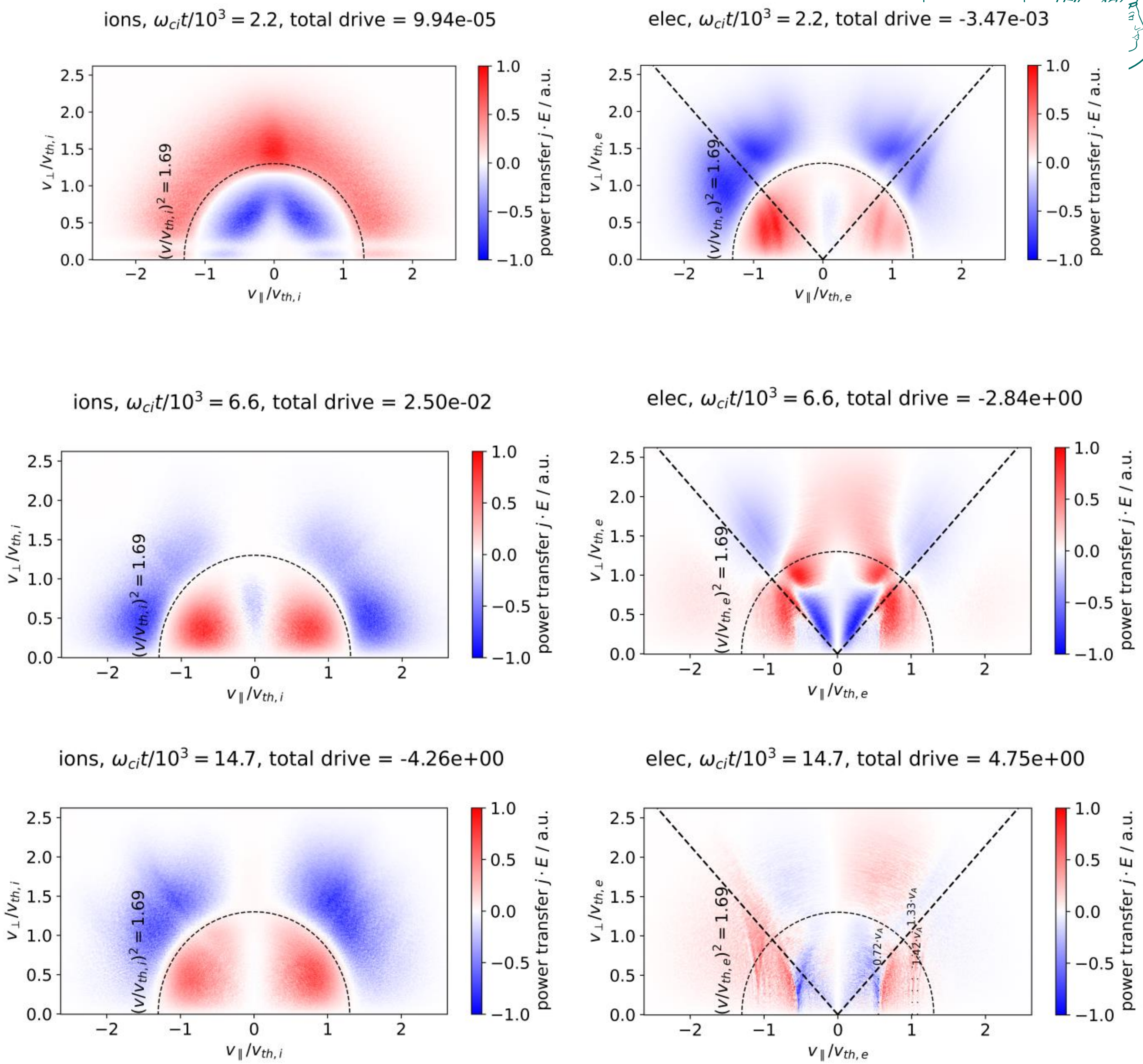
Backupslides

Turbulence perturbed rotational transform



Particle drive - $\beta = 4\%$

- **Tracking power transfer between fields and particles.**
  - Negative value => particles drive instability and v.v.
- **Transition from electron drive (early and intermediate phase) to ion drive (nonlinear phase).**
- **Early phase similar for all β-values, changes as β increases**
- **For electrons (all β): late stages show trapped particles (varies slightly with β) and $v_\parallel$-resonances (all β)**



Radial mode structure (electrostatic)

Electron mode

$\beta = 1\%$

ns	64 (No Padé)	64	512 (annulus)	512(annulus)
γ [10^5 s^-1]	4.76	9.23	10.85	10.64
ω [10^5 Hz]	-2.24	+2.12	+2.30	2.35
m	71	75	75	74
N per cell	114	114	76	171