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FÜR PLASMAPHYSIK

Turbulence Suppression in JET D–T Plasmas

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EUROfusion

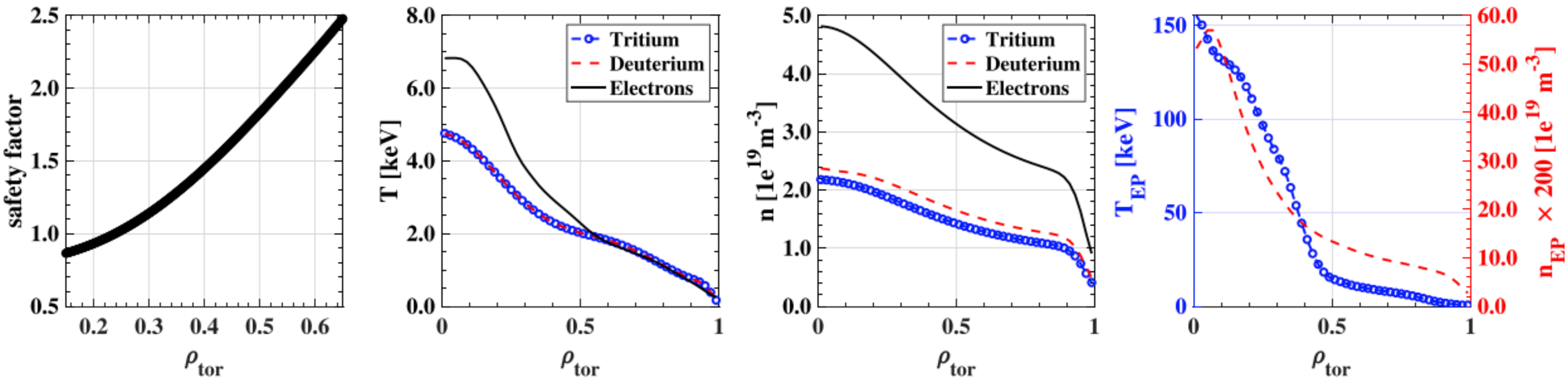
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Overview

- Introduction and Experimental Scenario
- Simulation Setup and Linear Analysis
- Turbulence Suppression Mechanisms
    - Wave-particle “resonance” effects
    - TAE Effects on Turbulence and Heat Flux
    - Zonal Flows, Currents, Cross-Phase Modifications and Profile Relaxation
- Quantitative Stabilization
- Summary

JET Discharge 99896

- D–T plasma (~50/50), R0 =3m, a =0.91m, low rotation.
- Mainly ICRH (MeV fast ions, ~1% H minority) + auxiliary NBI.
- TAE modes are observed experimentally.
- Temperatures/densities from CXRS, LIDAR, HRTS.



(a) (b) (c) (d)

- Realistic ion/electron mass ratios & electromagnetic effects.
- Block-structured velocity grid resolves fast-ion temperature gradients
- Domain & Resolution: $\rho_{tor} = [0.15, 0.65]$, $(n_x, n_y, n_z) = (384 \times 64 \times 32)$

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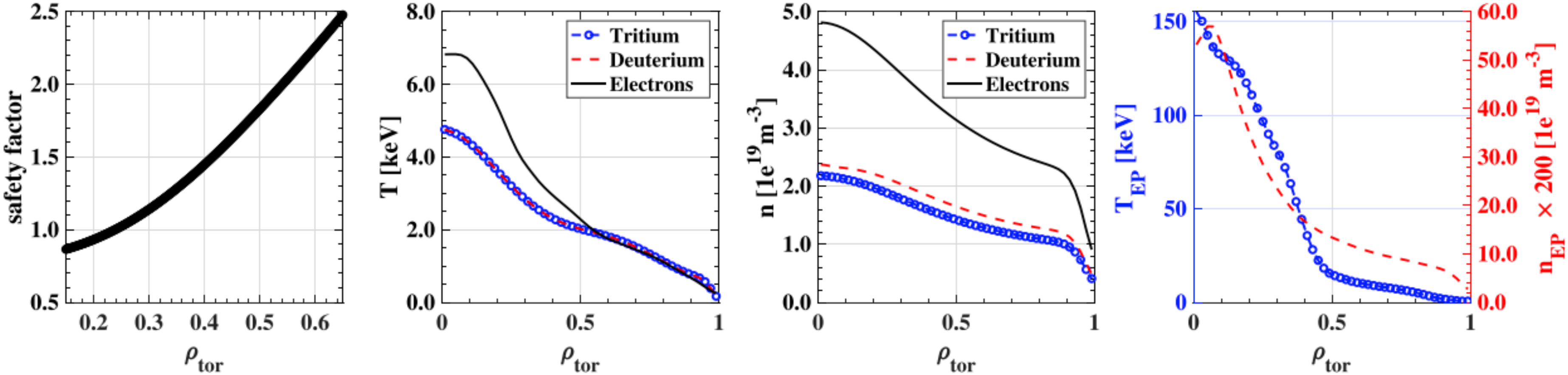

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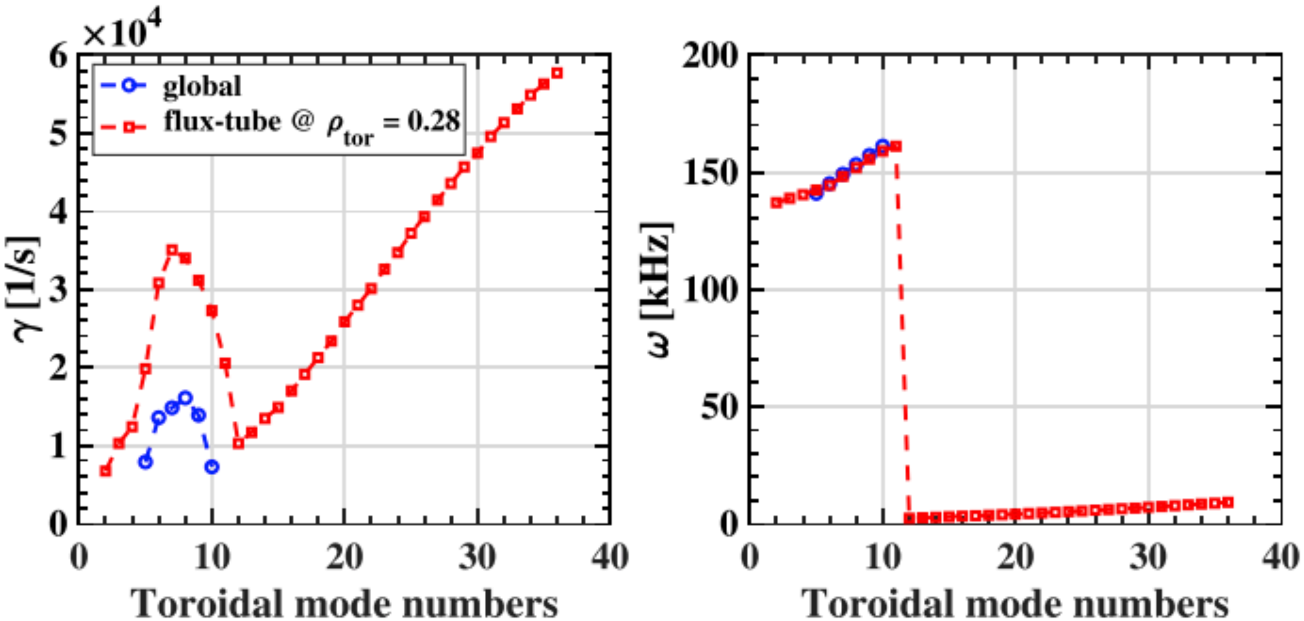
Linear TAE Stability Analysis

- Simulations are performed using both the radially global GENE and the local GENE at the radial location where the TAE is most unstable in the global run.

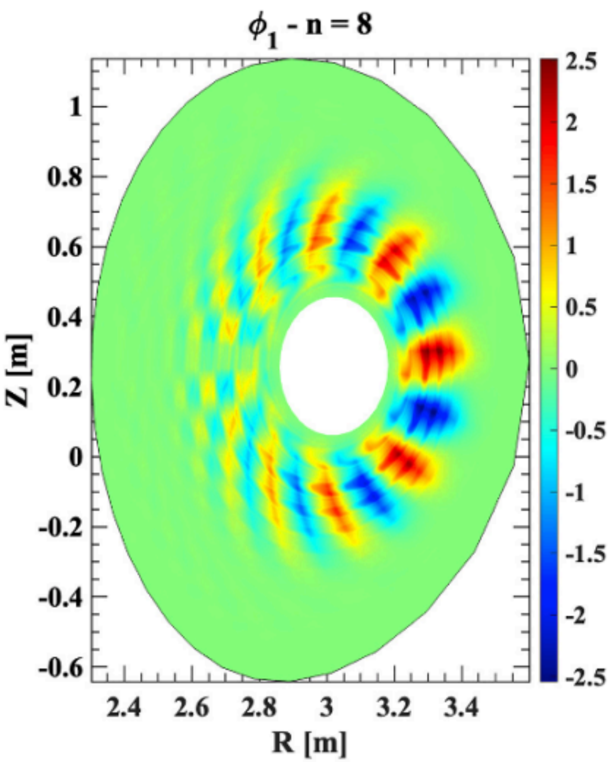


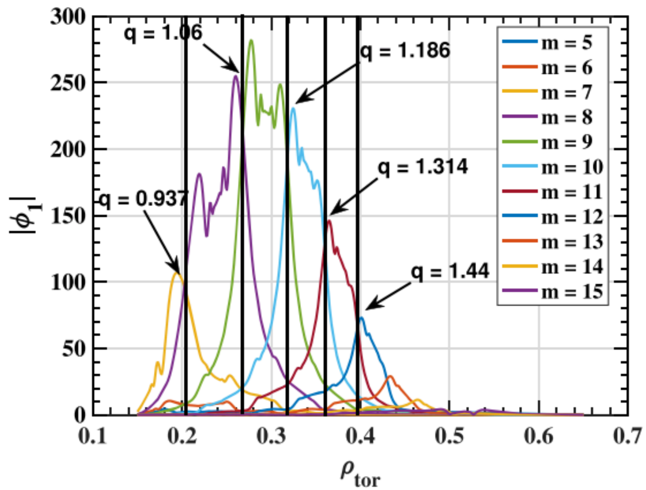
(a) (b)

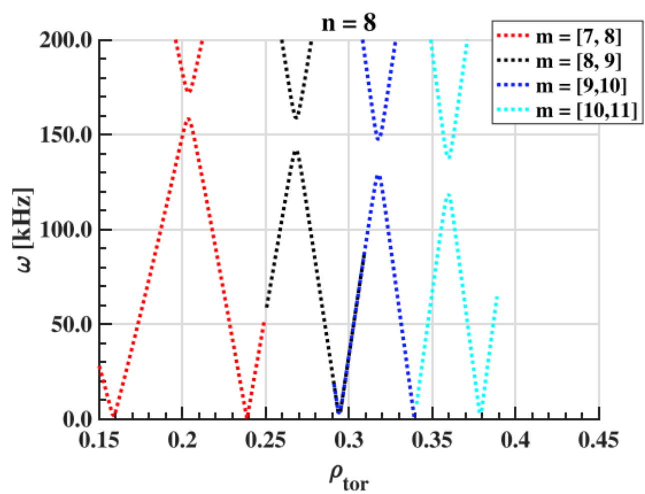
- Local model reproduces mode frequency well.
- Growth rate overestimated (~factor 2) due to missing profile shaping and limited local approximation.

Mode Structure & TAE Identification

- Poloidal cross-section (n = 8) shows multiple harmonics.







- Alfvén continuum analysis confirms modes are TAEs in gaps (ω≈150 kHz).
- These results are consistent with experimental observations.

Turbulence Suppression Mechanisms

Wave-Particle Resonance Effects

- Energetic particles interact with ITG instabilities via wave-particle resonance.
- Supra-thermal particles can interact with ITGs when fast ion magnetic drift frequency $\omega_{d,f}(\propto B_0 \times \nabla B_0)$ is close to the linear ITG frequency ω_k.

Resonant interaction:

1. energetic particles can resonate with the background instabilities if

$$\omega_k \approx \omega_{d,f}$$

$\omega_{d,f}$ is controlled by T_f

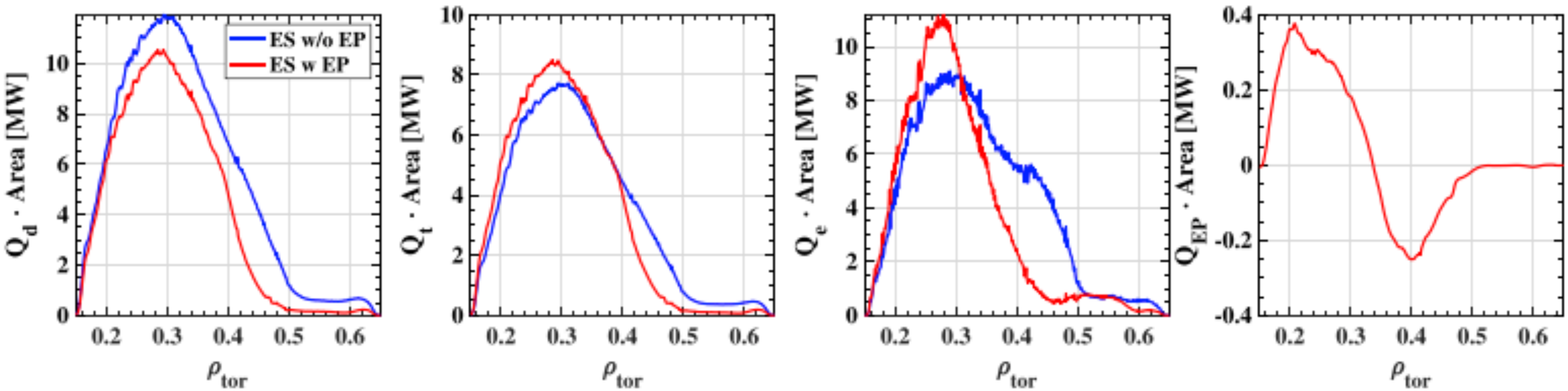
2. effective stabilisation only if

$$\left|\frac{R}{L_{n,f}}\right| \ll \left|\frac{R}{L_{T,f}}\right|$$

Condition typically matched by ICRH fast ions

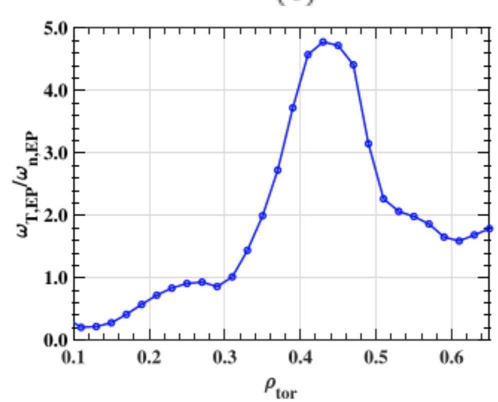
Wave-Particle Resonance Effects

- To isolate this effect, we perform radially global ES Gene simulations with and without EPs.
- Wave-particle resonance leads to significant reduction in ITG-driven turbulence.
- Up to 80% reduction in turbulent fluxes observed in optimal radial regions.



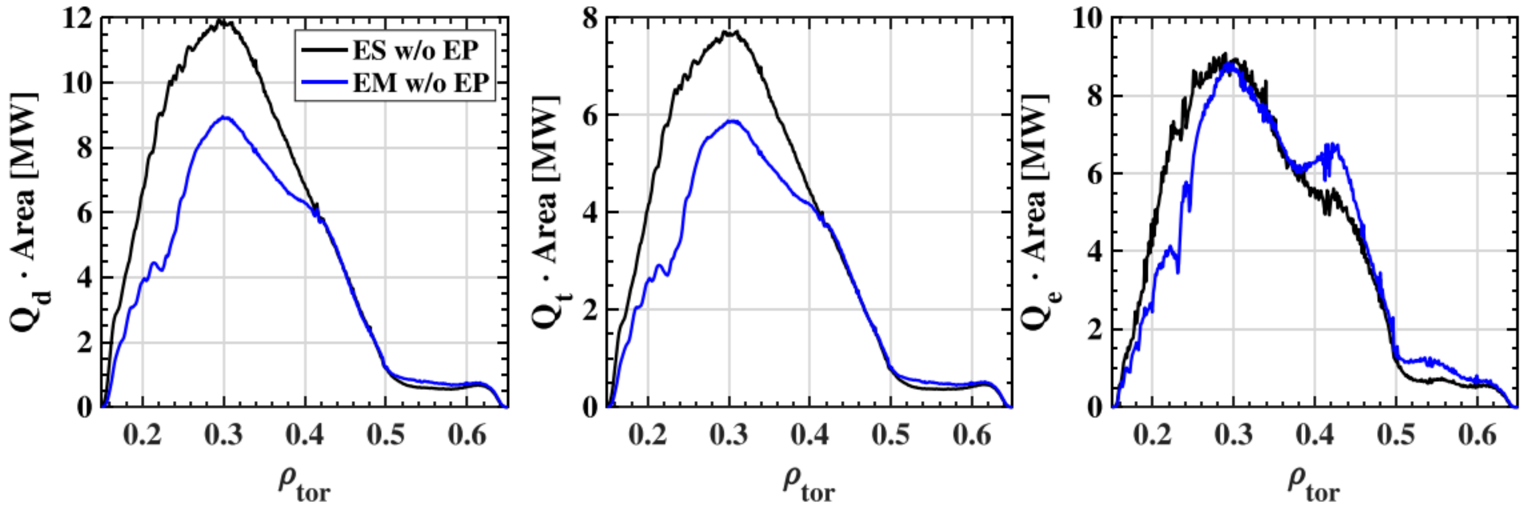
(a) (b) (c) (d)

- Maximum suppression aligns with regions of strong temperature gradient.



Electromagnetic Beta Stabilization

- To isolate this effect, we perform radially global ES and EM Gene simulations without EPs.
- Electromagnetic effects reduce turbulence even without fast ions.

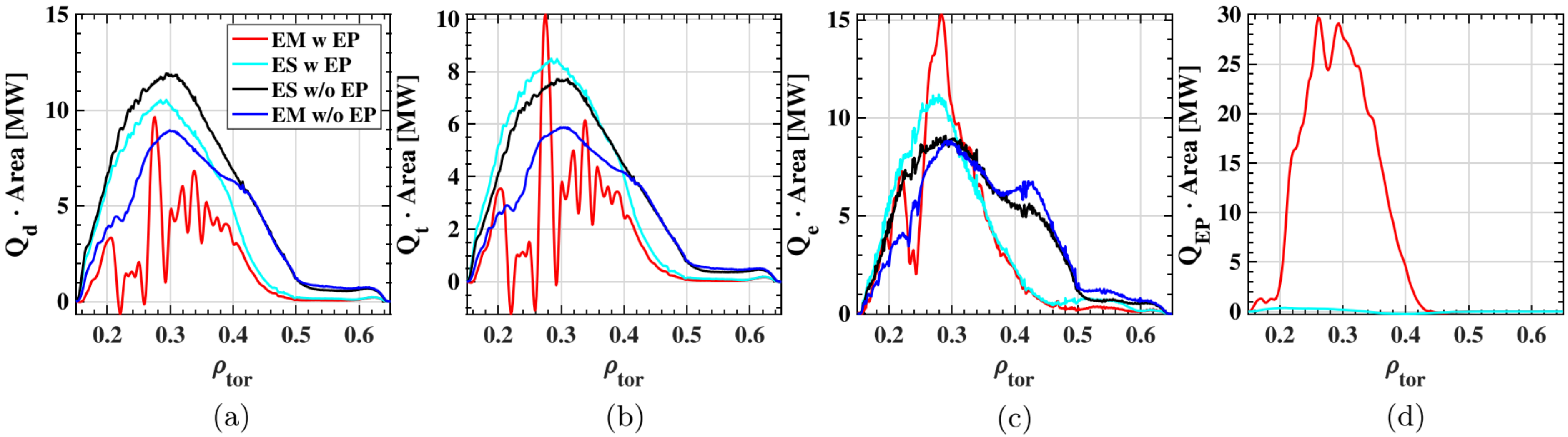


(a) (b) (c)

- Observed 30–40% reduction in turbulent fluxes for ϱtor < 0.4, which is the region where ITG modes dominate: for ϱtor < 0.35; TEMs for 0.35 < ϱtor < 0.55

TAE-Driven Turbulence Suppression

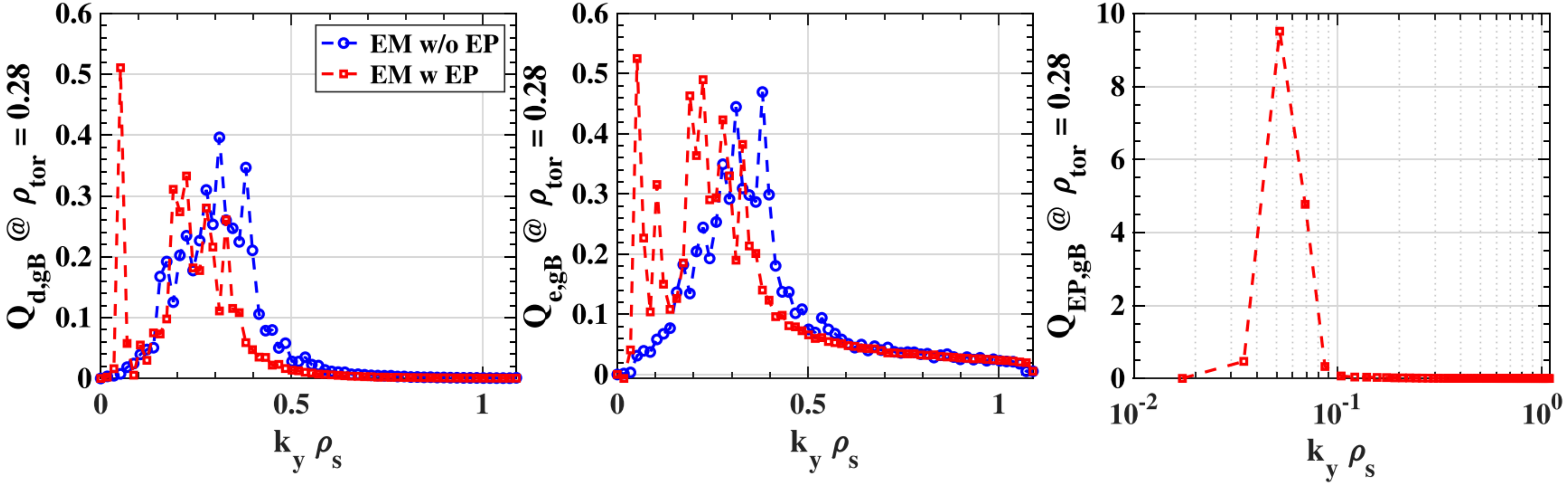
- To isolate this effect, we perform radially global ES and EM Gene simulations with EPs.
- TAEs generate fine radial oscillations in turbulent flux profiles.
- High-frequency fluctuations observed in thermal species during TAE activity.



- TAEs stabilize thermal ion fluxes but increase energetic particle fluxes.
- Energetic particle heat flux exceeds thermal fluxes in TAE-dominated regions.

TAE-Driven Turbulence Suppression

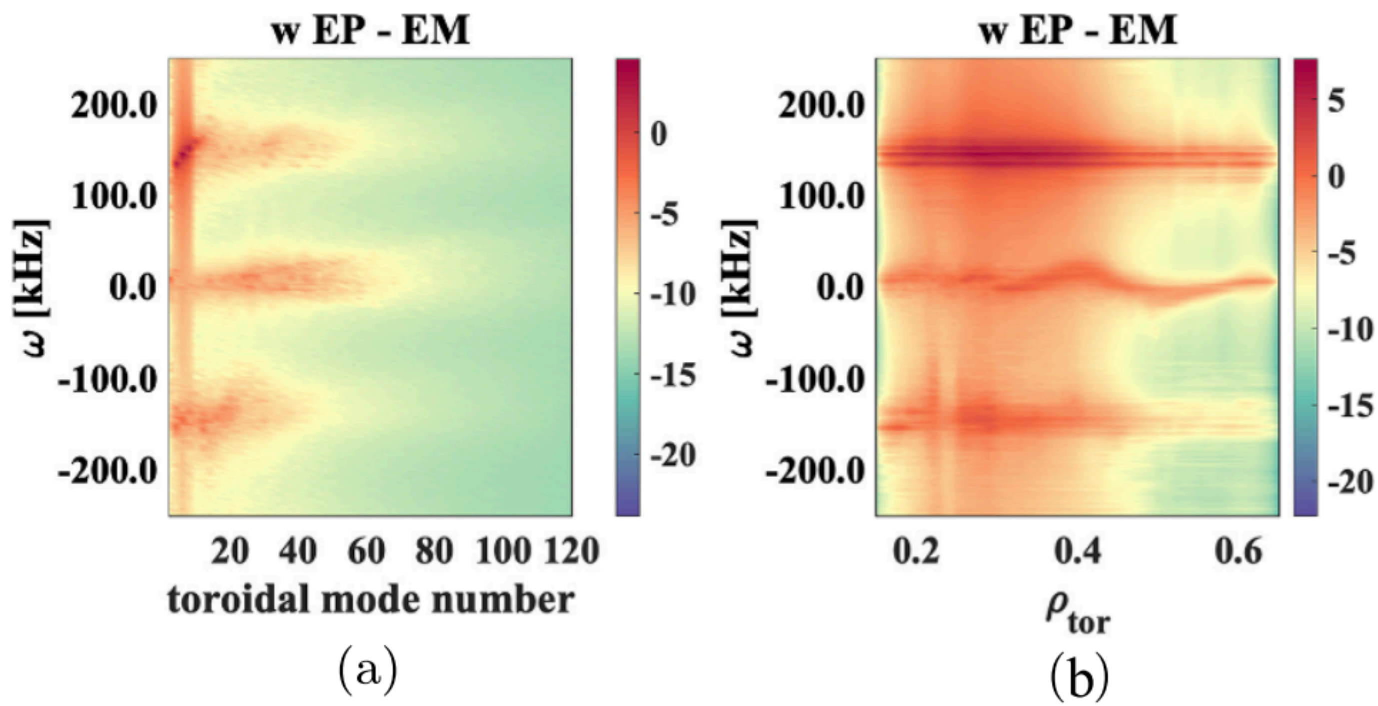
- TAEs move heat flux to lower kyϱs, especially at n=6 and n=8.
- Enhanced flux observed at TAE-dominated scales.



- TAEs introduce larger meso-scale structures in turbulence.
- Turbulence regime transitions from drift-wave to TAE-dominated.

TAE-Driven Turbulence Suppression

- Nonlinear TAE frequencies closely match linear simulation results
- Frequency spectra confirm TAE modes are unstable



- TAE remains unstable throughout simulation, indicating sustained activity
- TAE frequency shows gradual decrease over time with frequency oscillations linked to energetic particle profile relaxation

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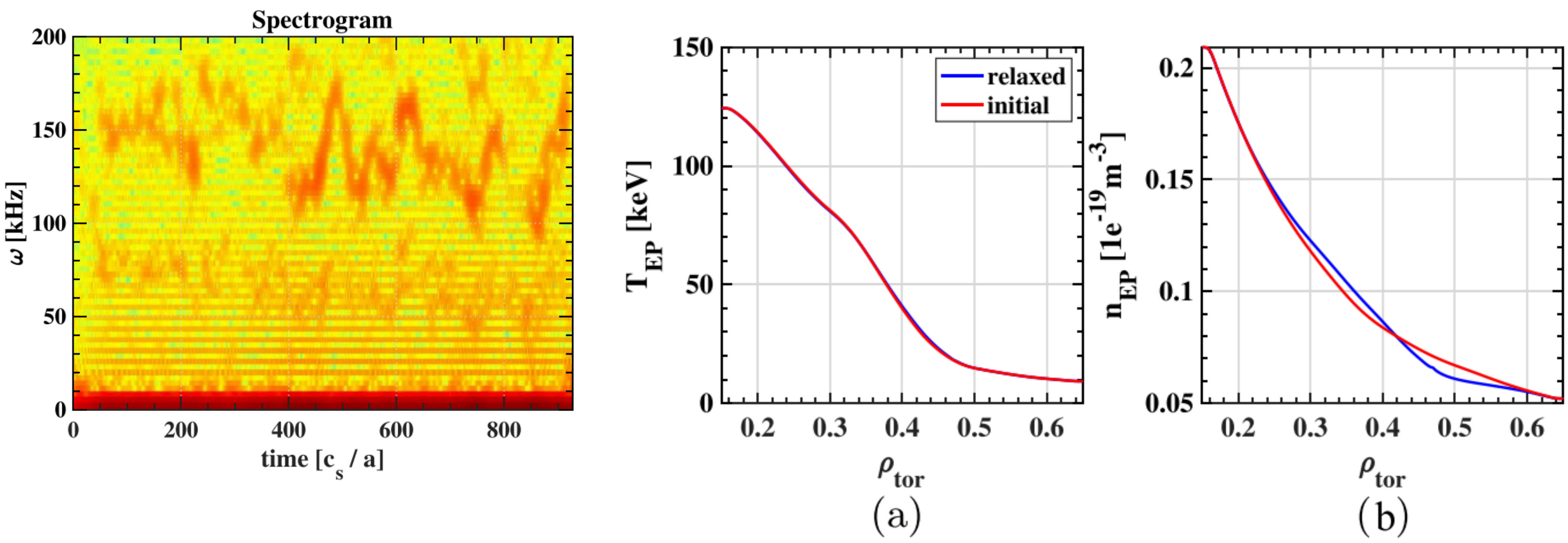

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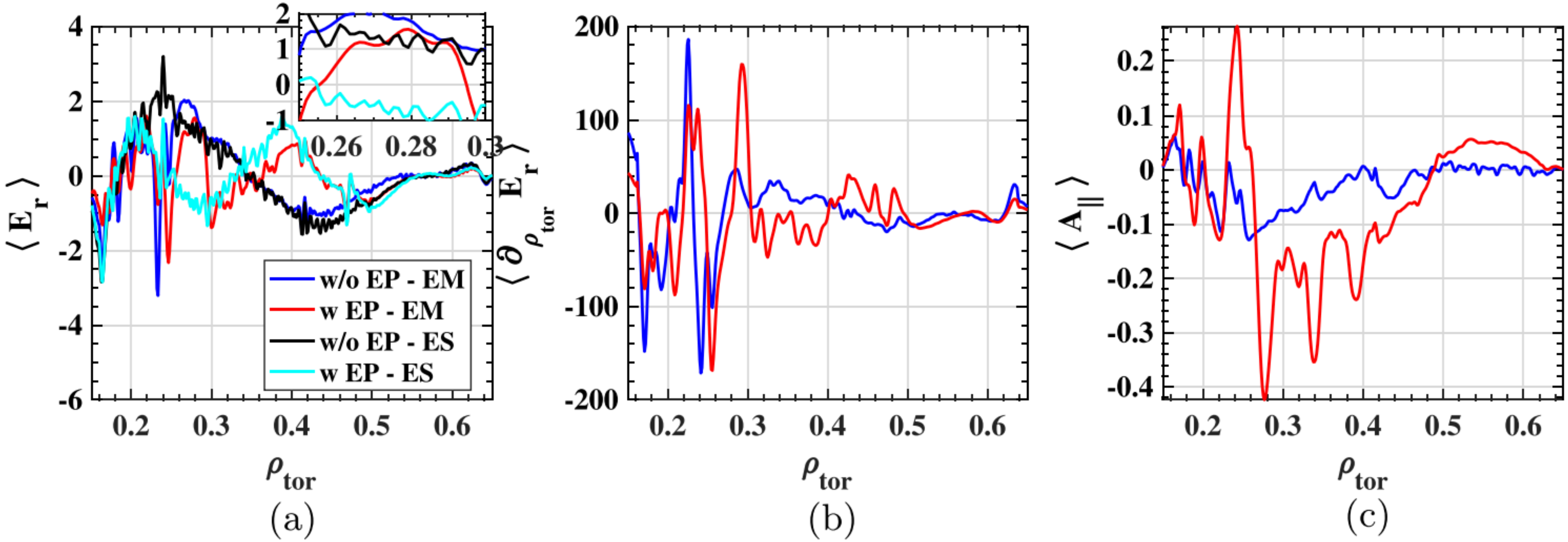
Zonal Fields Enhancement in the presence of TAEs

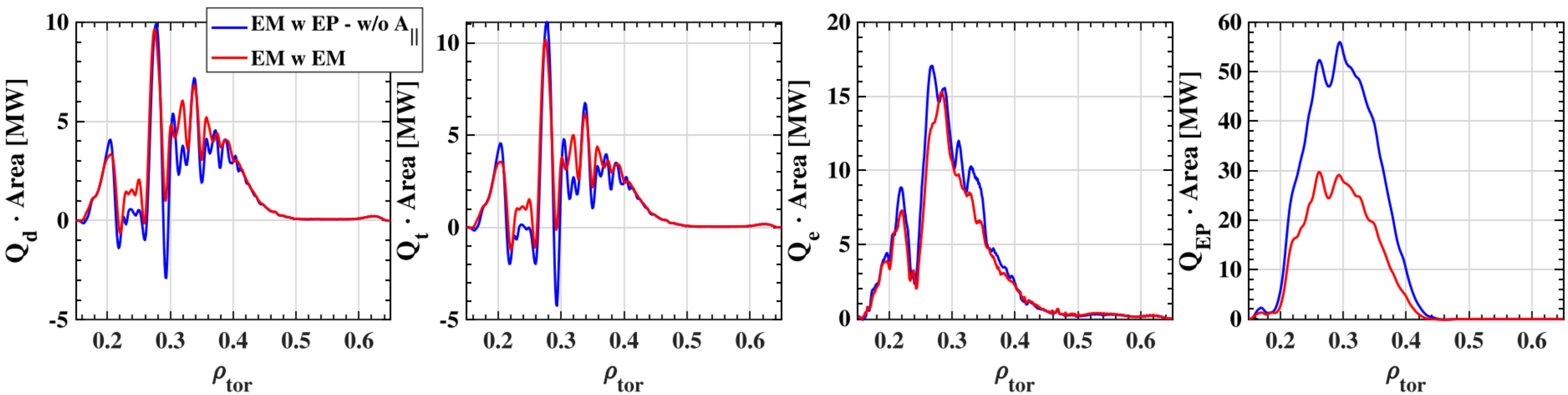
- TAEs cause a localized increase in the flux-surface-averaged radial electric field at the position where the TAE mode is most unstable at ϱtor ≈ 0.28, coinciding with the peak of the TAE mode structure.



- Radial derivative of the electric field increases by a factor of 15 at the TAE location.
- Zonal currents are also amplified by the TAE at each harmonics.

Zonal Fields Enhancement in the presence of TAEs

- Artificial removal of zonal currents leads to a doubling of energetic particle flux.
- Despite increased energetic particle transport, thermal ion and electron fluxes are largely unaffected.

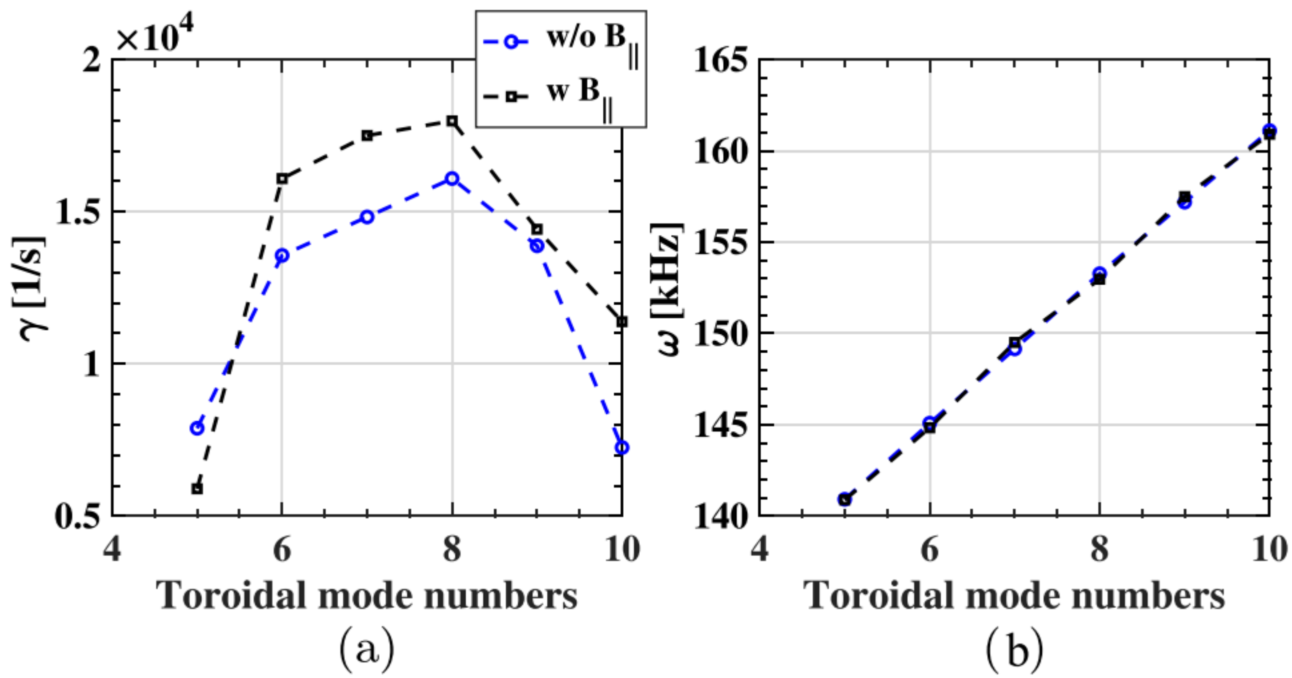


(a) (b) (c) (d)

- Zonal currents play a key role in self-regulating the radial electric field during TAE saturation.
- Zonal flows and zonal currents are strongly coupled, making their individual effects difficult to isolate.

Parallel Magnetic Fluctuations

- Including B||, increases TAE growth rate by 20%
- Mode frequencies remain largely unchanged



- Minimal effect on saturated turbulent fluxes
- Thermal and energetic particle fluxes similar with or without B||

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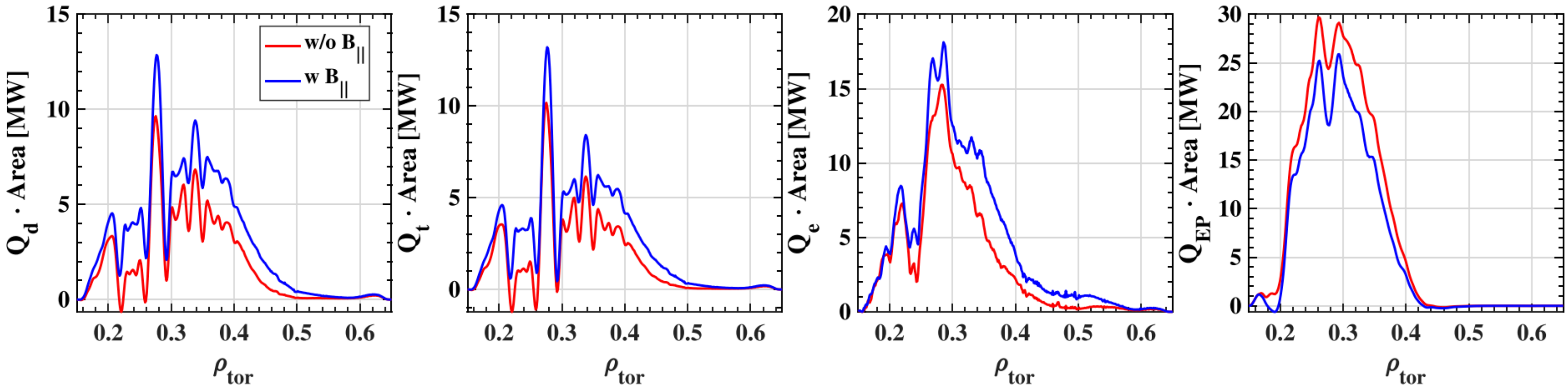

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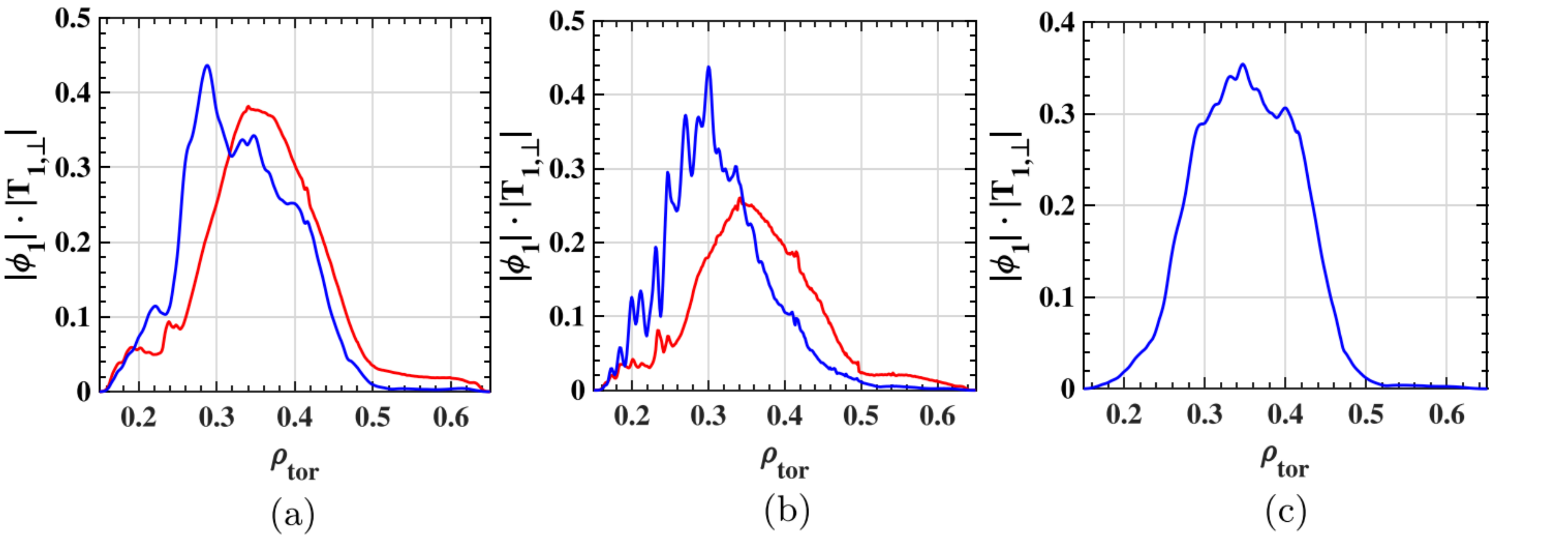
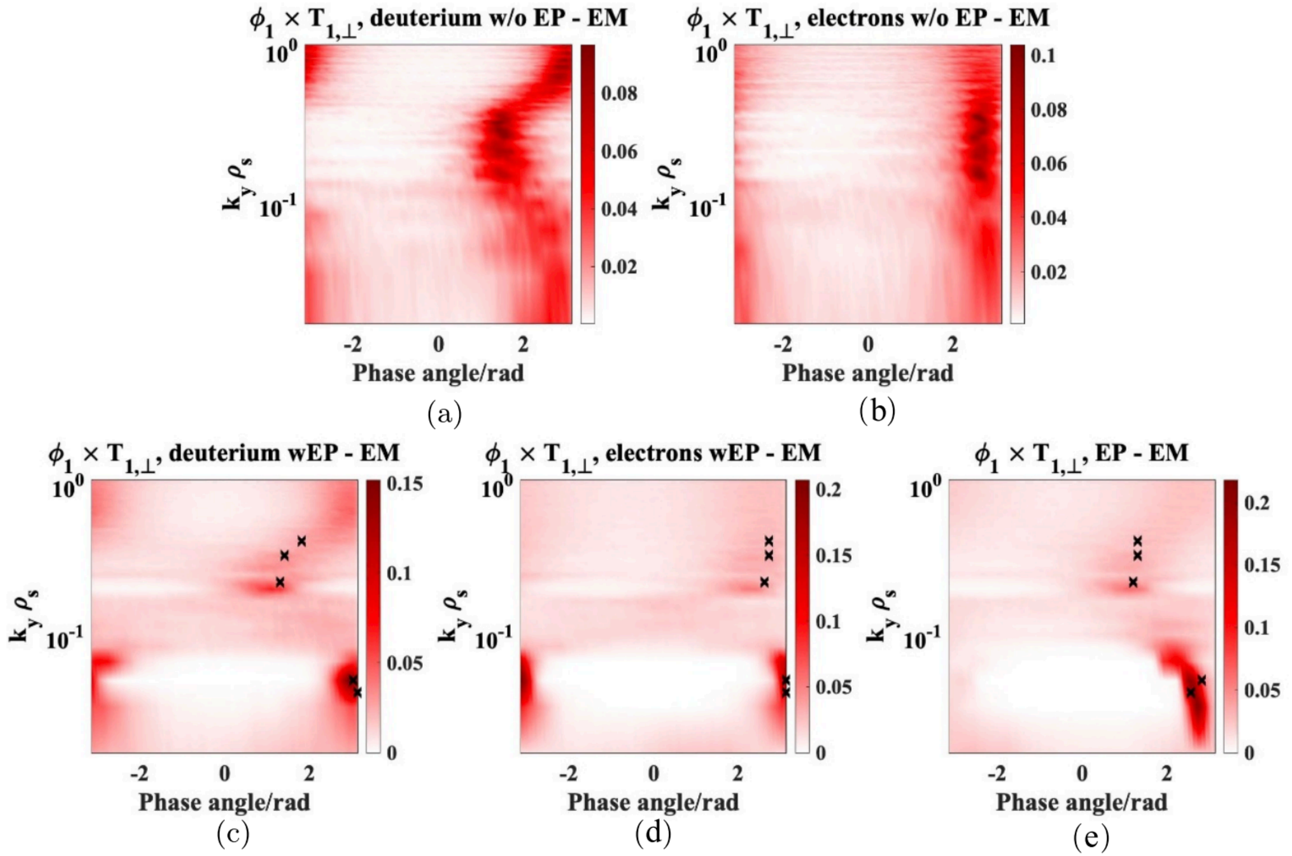
Cross-Phase Modifications by TAEs

- Electron fluctuation amplitudes increase with TAEs; thermal ion amplitudes remain largely unchanged.



- TAEs shift cross-phase between temperature and electrostatic potential to nearly π at TAE scales, changing turbulence characteristics.
- Cross-phase modifications alone do not fully explain the observed reduction in turbulent transport.

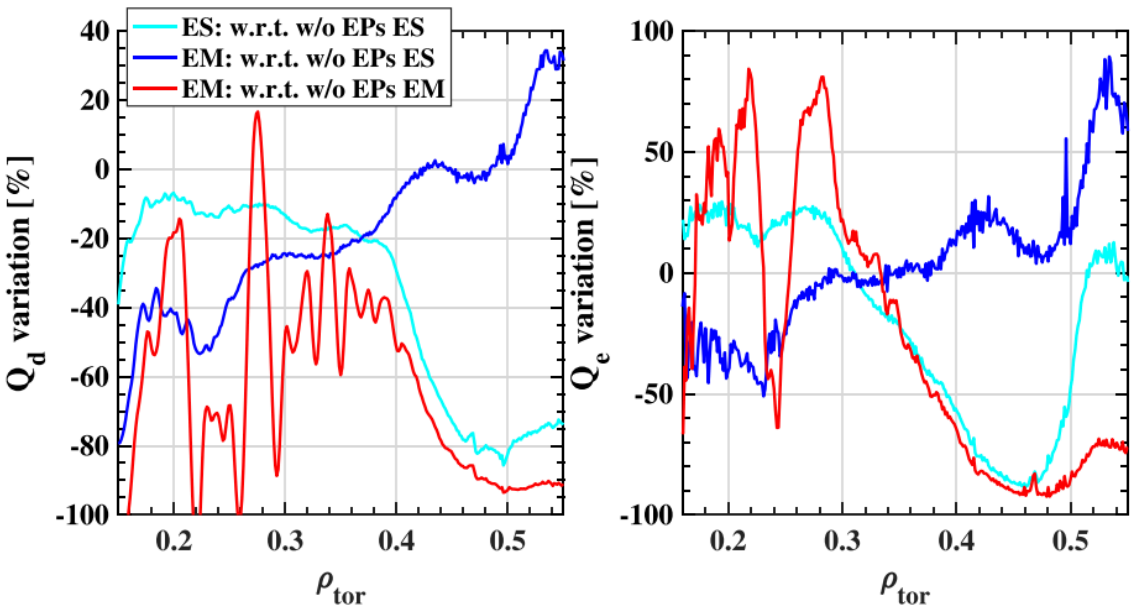
Cross-Phase Modifications by TAEs



- TAEs shift cross-phase between temperature and electrostatic potential to nearly π at TAE scales, changing turbulence characteristics.
- Cross-phase modifications alone do not fully explain the observed reduction in turbulent transport.

Quantitative Comparison of Stabilization Effects

- Wave-Particle Resonance: produces up to 80% reduction at mid-radius → effective where energetic particle temperature and gradient are optimal.
- Electromagnetic Beta Stabilization: provides 20–30% reduction in the deep plasma core → stabilization strongest for ϱtor < 0.4, where plasma beta is larger.
- TAE-Induced Turbulence Suppression: causes up to 80% suppression of turbulent fluxes in the deep core.



(a) (b)

Summary of Key Findings

- Distinct mechanisms act at different plasma radii to suppress turbulence for this JET D-T discharge.
- Resonant interactions reduce turbulent fluxes by up to 80% in outer core regions.
- Beta stabilization provides an additional 20–30% reduction in turbulence, mainly in the deep core.
- TAEs further decrease fluxes by up to 80% in the deep core, shifting turbulence regime.
- TAEs induce a shift from drift-wave to TAE-dominated turbulence, modifying cross-phase relationships.