Cross-scale Interaction between Microturbulence and Meso-scale Reversed Shear Alfven Eigenmode in DIII-D Plasmas

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Outline

- Motivations

- Global simulations in DIII-D shot #159243------ New physics of cross-scale interaction underling EP transport & Validation of GTC nonlinear EM model

- Global simulations in ITER steady state scenario #131041------Prediction of α particle confinement in burning plasmas

Confinement of EP determines the performance of future burning plasmas

- EP produced by heating source and fusion reaction can excite AE
- Anomalous EP loss cause by AE reduces the heating efficiency and threatens 'ignition' condition
- The performance of future fusion reactors is crucially dependent on the good confinement of EP
- Understanding the AE & EP on existing machines is needed for extrapolating EP confinement properties to burning plasma

- W. W. Heidbrink, Physics of Plasmas 27, 055501 (2008)
- P. Lauber, Physics Reports 533, 33 (2013)
- L. Chen and F. Zonca, Reviews of Modern Physics 88, 015088 (2016)

Prediction of EP transport requires integrated simulations

- Strong coupling of EP with thermal plasmas leads to uncertainties on the explanation of AE nonlinear dynamics and EP confinement
- Simulations of EP coupling with thermal plasmas must incorporate microturbulence and MHD instabilities with kinetic effects of both EP and thermal plasmas on an equal footing.
- EP transport prediction is based on the progression from linear dispersion to nonlinear dynamics and eventually to EP transport
- Selected well diagnosed DIII-D discharge #159243, linear V&V studies have been achieved
- Nonlinear validation studies in DIII-D and extrapolating to ITER are reported here

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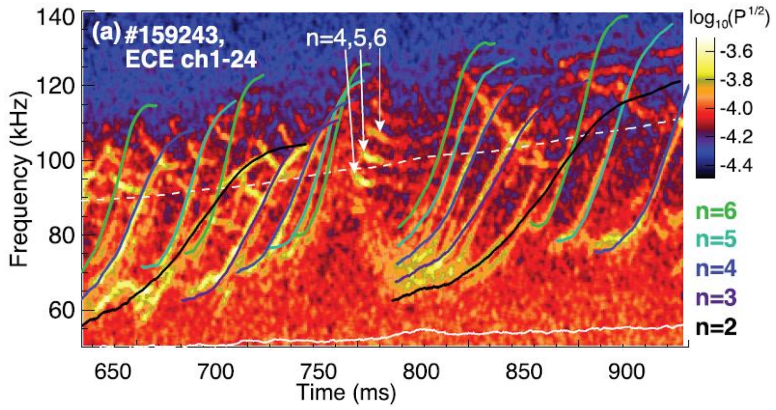
- C. Collins et al., Physics Review Letters 116, 095001 (2016)
- S. Taimourzadeh et al., Nuclear Fusion 59, 066006 (2019)

Outline

- Global simulations in DIII-D shot #159243-------- New physics of cross-scale interaction underling EP transport & Validation of GTC nonlinear EM model

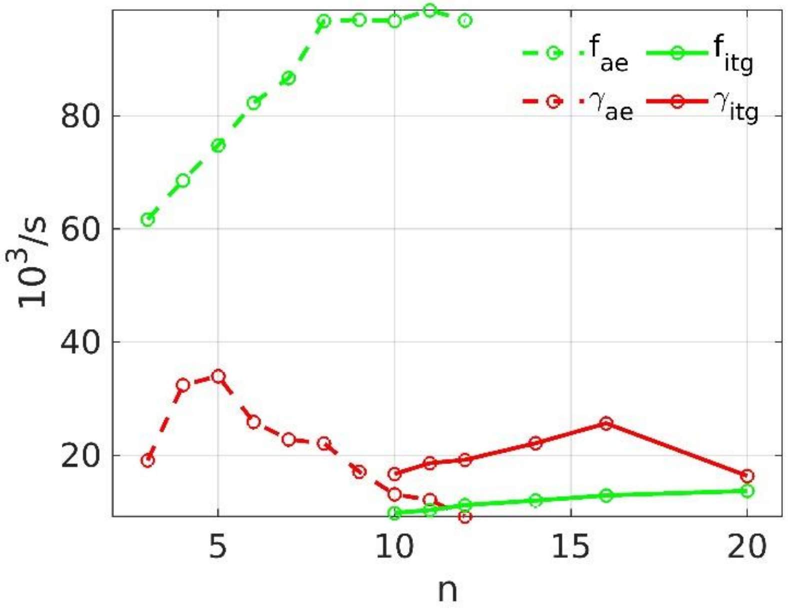
Co-existence of RSAE & ITG in DIII-D shot # 159243

- AE in DIII-D #159243



- High-n ITG have **smaller** f and γ; broader mode structure overlapping with RSAE

- Low-n RSAE have **larger** f and γ; mode localizes near q_{min}

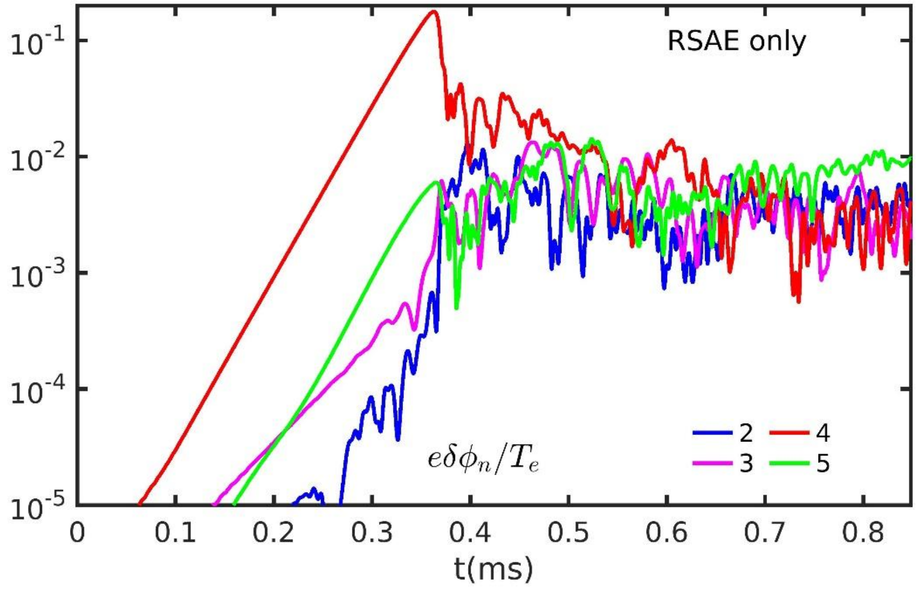


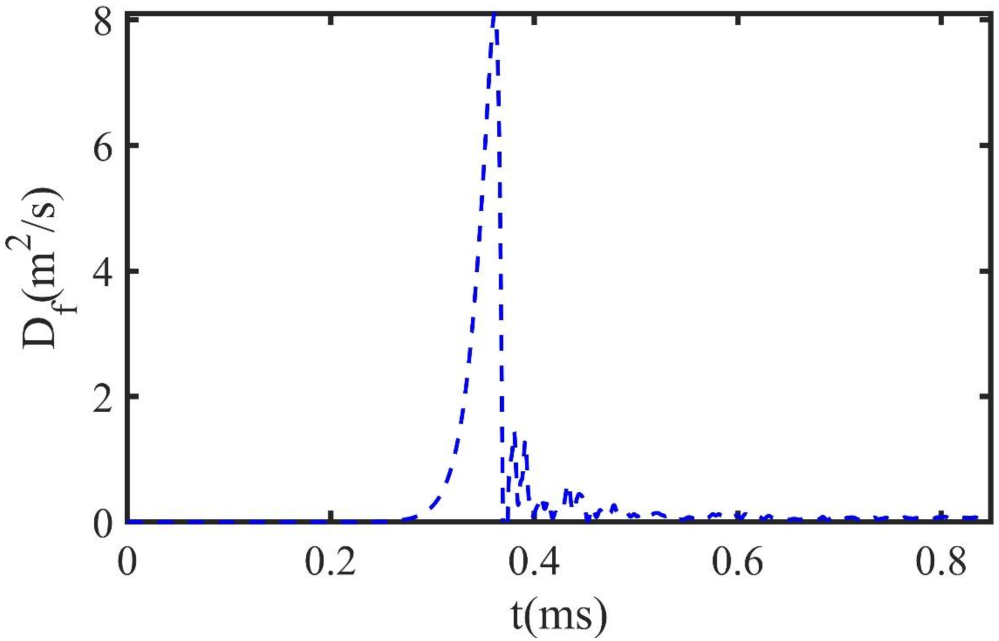
- RSAE $n = 4{,}5$ dominate
- ITG $n = 14{,}16$ dominate

- H. Wang et al., Plasma Sci. Technol. 23, 015101 (2021)

No steady state AE turbulence and EP transport in single scale simulation

- Multiple-n simulation n=0-10 & dominant nonlinear mode n=4,5.
- Huge initial burst & quenched nonlinear phase also observed, no steady state, contradicting experiment.
- Coulomb collisional effects of EP negligible due to high temperature.





- P. Liu et al., Reviews of Modern Plasma Physics 7, 15(2023)

Cross scale coupling between microturbulence and AE

- EP scattering by microturbulence affect EP phase space dynamics
  - M3D-K shows that added diffusivity plays similar role as collision in TAE saturation
  - RBQ shows that large pitch angle scattering due to microturbulence can lead to steady state AE amplitude evolution
- Zonal fields generated by and self-regulation of both AE and microturbulence
  - GYRO shows that saturation of TAE/EPM needs zonal flow from stronger ITG/TEM
- Nonlinear generation of KAW due to scattering of TAE by DW can improve the α particle confinement

- E. M. Bass et al., Physics of Plasmas 17, 112319 (2010)
- J. Lang et al., Physics of Plasmas 18, 055902 (2011)
- N. N. Gorelenkov et al., Physics Letters A 386, 126944 (2021)
- L. Chen et al., Nuclear Fusion 62, 094001 (2022)

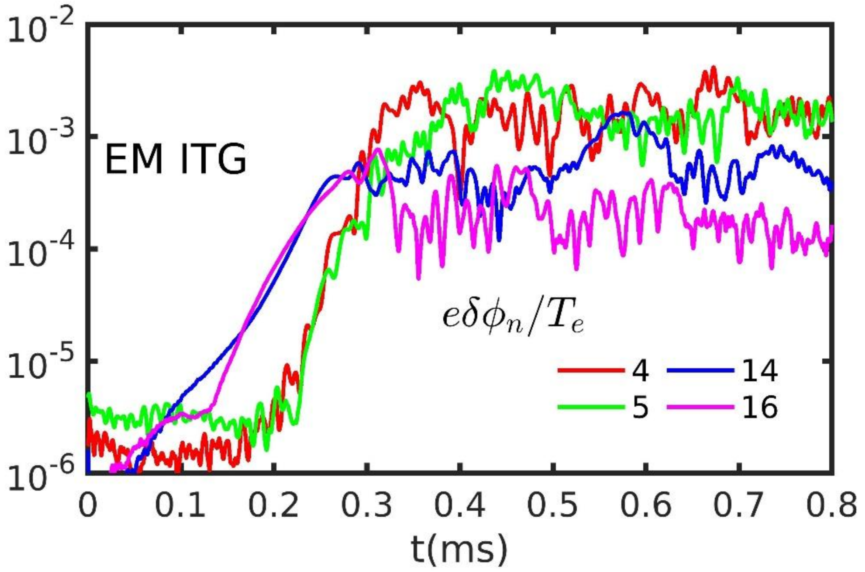
Nonlinear dynamics of electromagnetic ITG

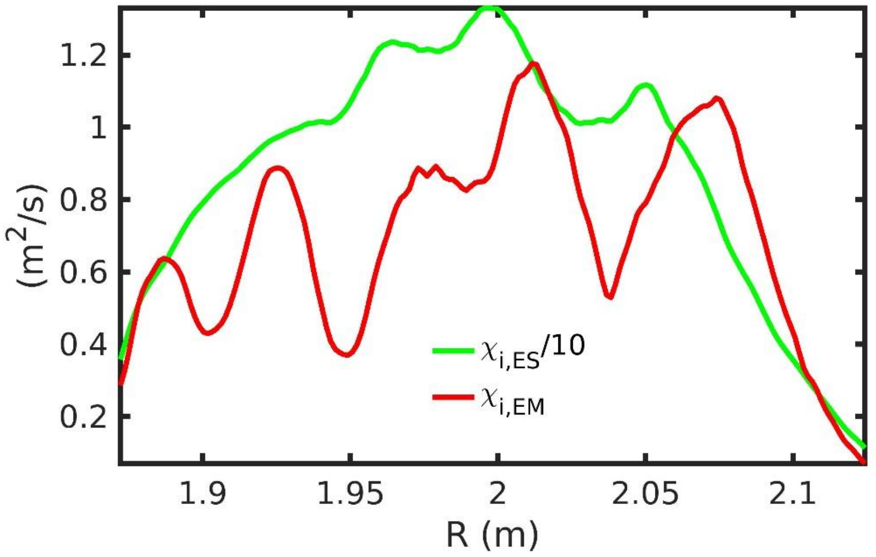
- EM ITG simulation (n=[0,25]) without EP

- Linearly stable ITG force driven by strong unstable ITG

- Thermal ion heat conductivity $\chi_i \sim 1\, m^2/s$

- χ_i exhibit a lower value at $q = 3$ resonant surfaces

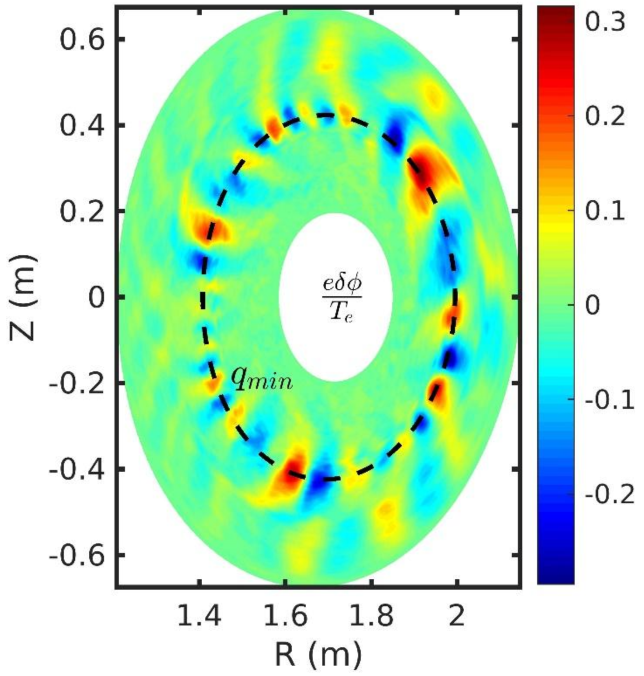


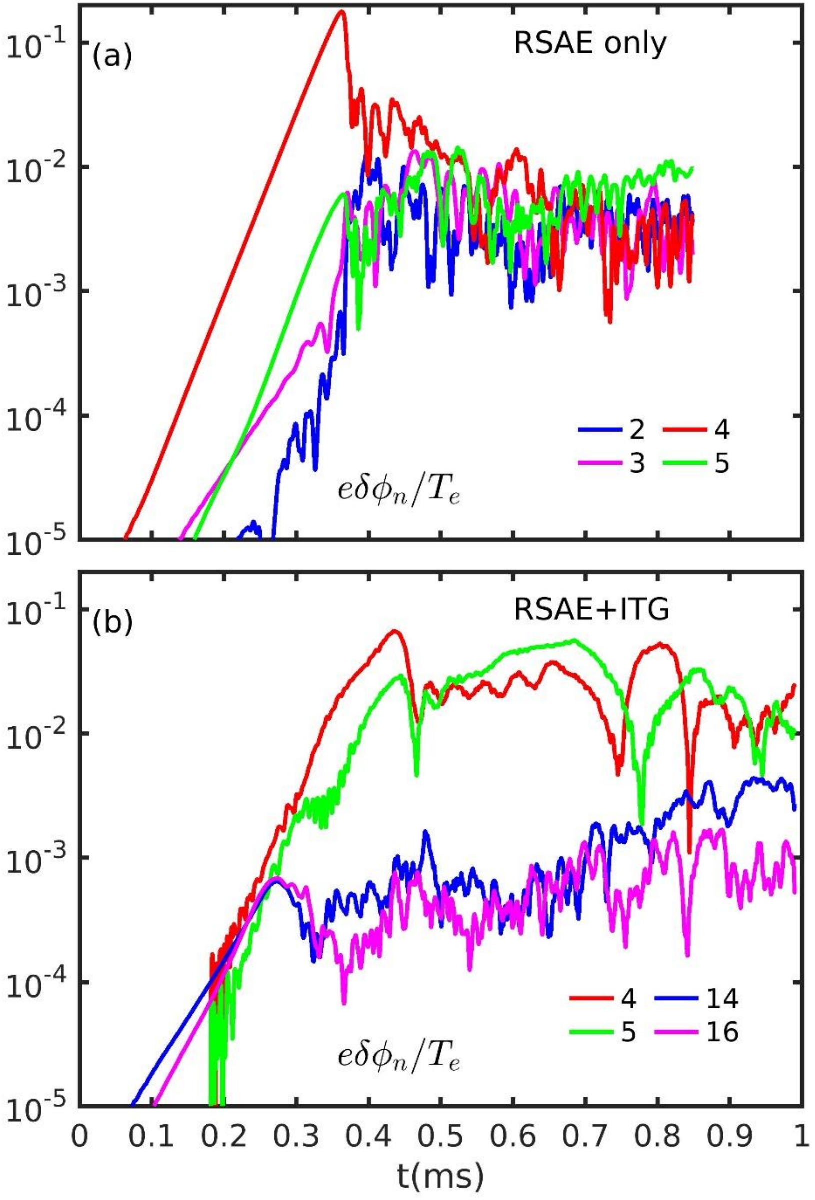


- P. Liu et al., Nuclear Fusion 64, 076007 (2024)

ITG microturbulence regulates RSAE

- Coupling ITG & RSAE (n=[0,25] with EP)
- ITG decrease the linear growth of RSAE
- ITG suppress the initial saturation of RSAE
- Quasi steady state RSAE
- Regular 2D mode structure in the nonlinear phase



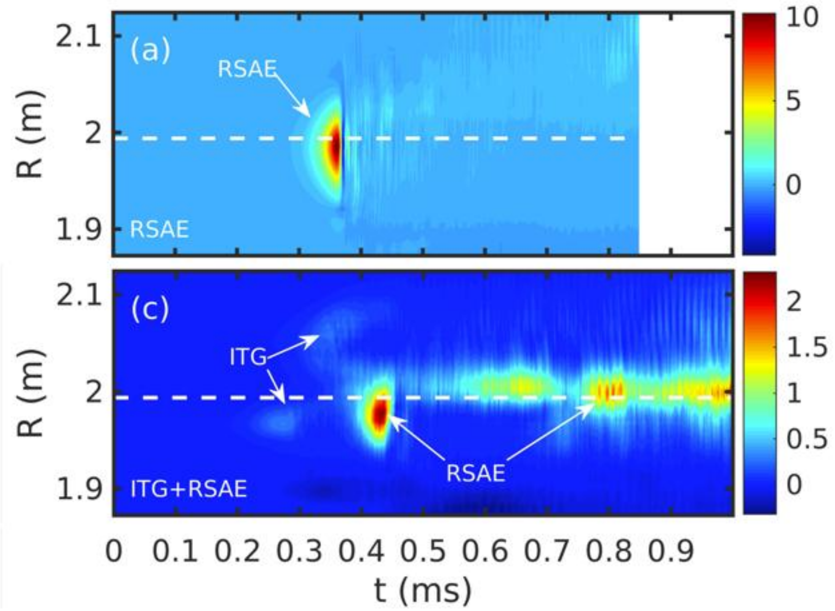


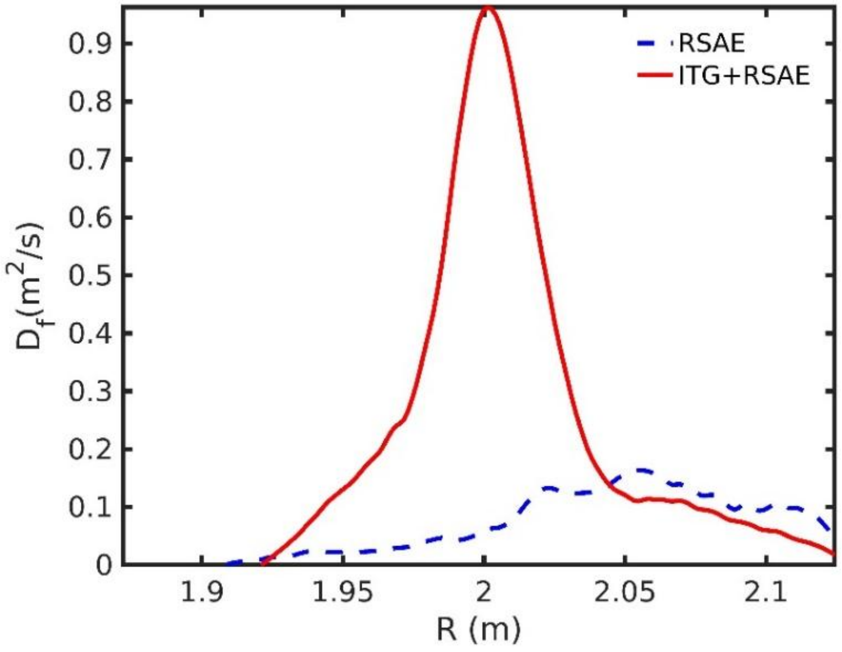
- P. Liu et al., Physical Review Letters 128, 185001(2022)

Quasi-steady state EP transport observed

- ITG reduces D_f by a factor of 5 at initial saturation of RSAE

- ITG enhances D_f to experimental level in nonlinear phase

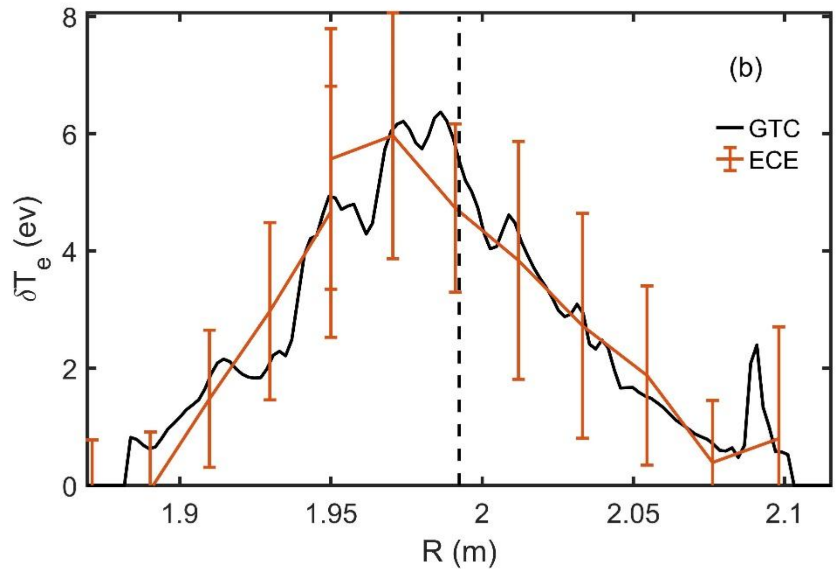




- P. Liu et al., Physical Review Letters 128, 185001(2022)
- P. Liu et al., Nuclear Fusion 64, 076007 (2024)

Simulation results agree with DIII-D measurement

- Radius structures and amplitudes of δT_e from GTC gyrokinetic simulation, for the first time, agree with ECE measurement in DIII-D



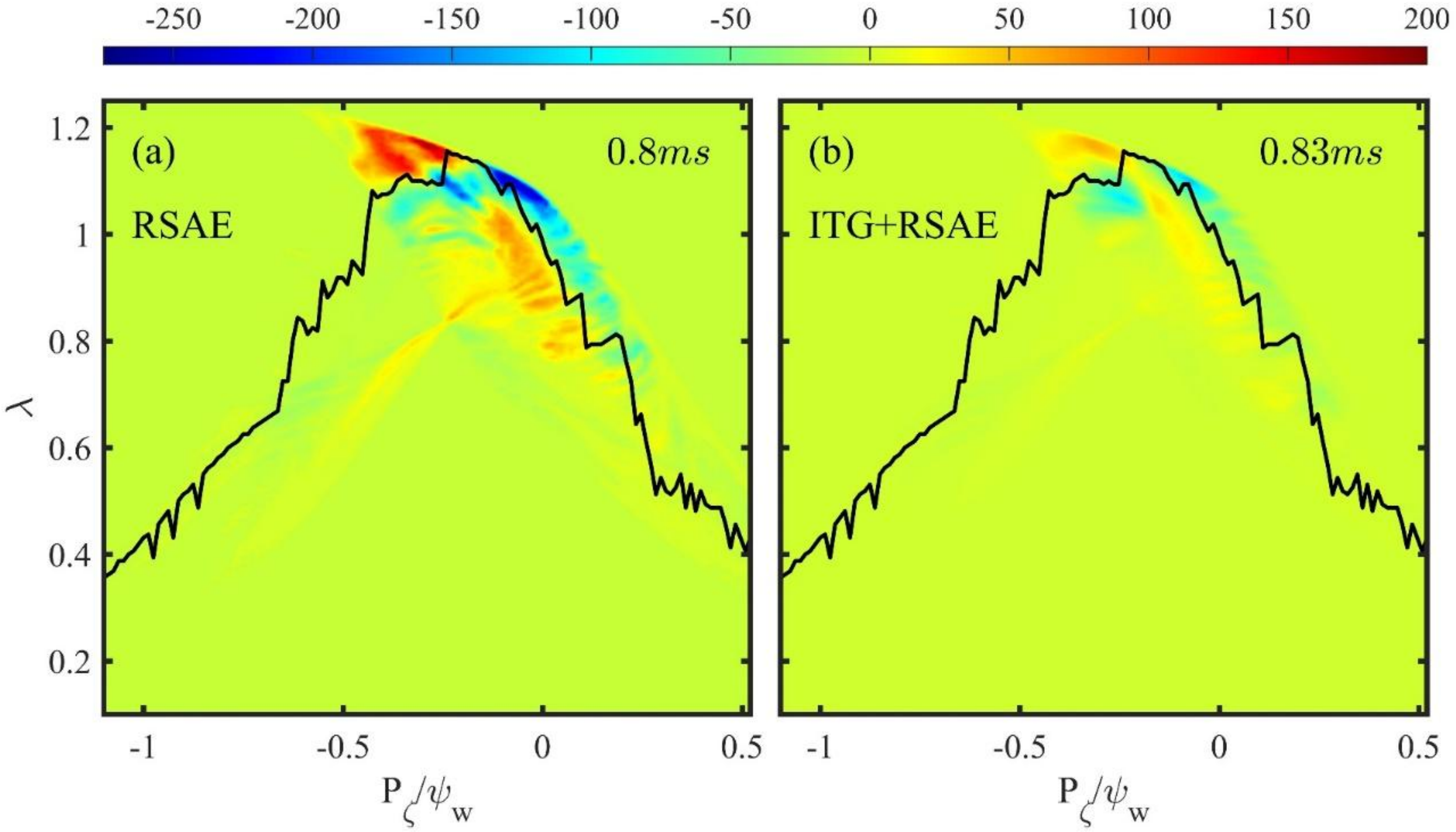
- Density fluctuations $\delta n_e/n_0 \sim 0.6\%$, close to BES measurement $0.3-0.4\%$

- $D_f \sim 0.8\, m^2/s$ has the right order of magnitude to TRANSP modeling value of $2m^2/s$

- P. Liu et al., Physical Review Letters 128, 185001(2022)
- W. W. Heidbrink, Physics of Plasmas 27, 055501 (2017)

Mechanism 1: ITG scatters nonlinearly trapped EP

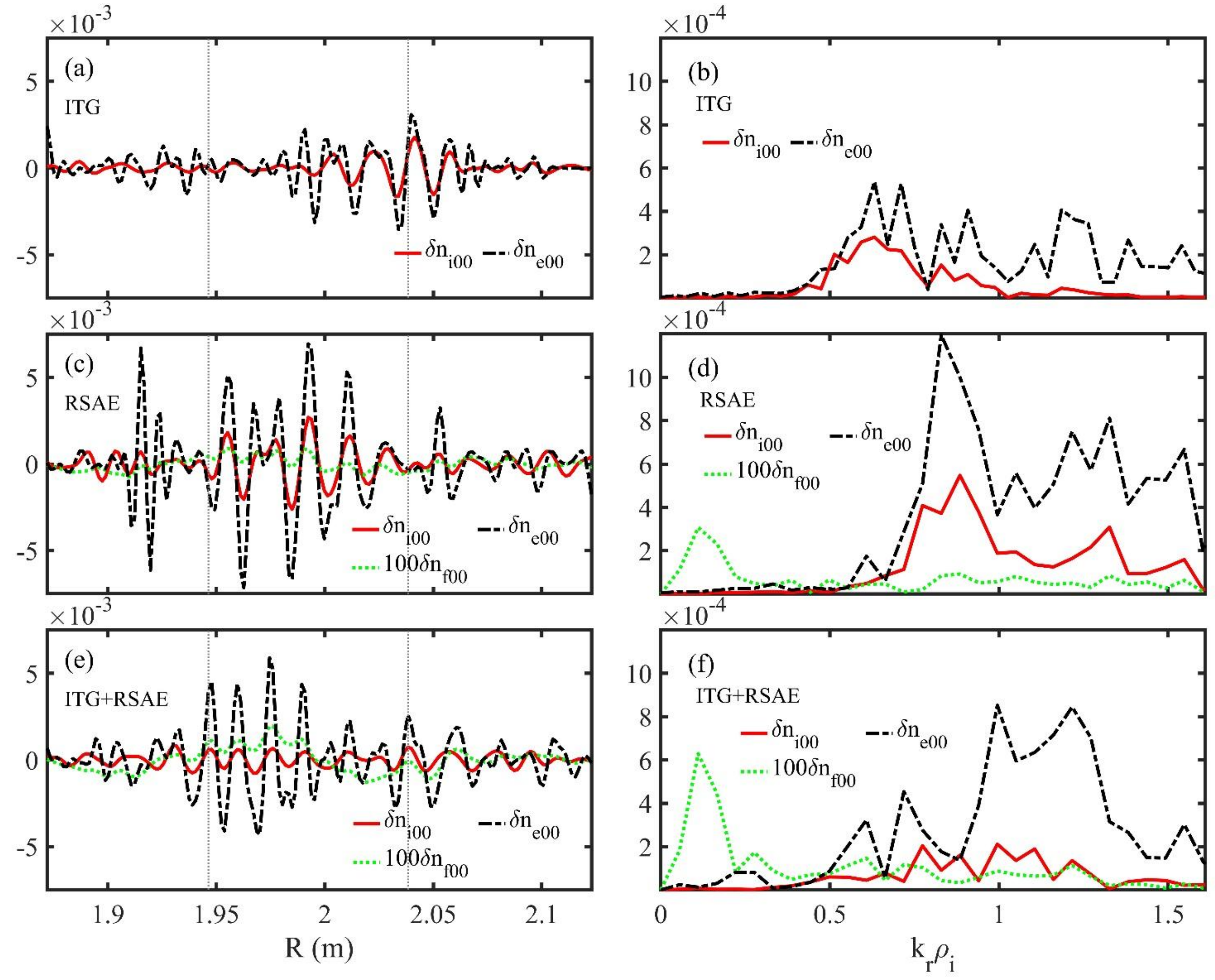
➢ EP scattering by ITG restores EP profile, resulting in quasi-steady state AE turbulence



- P. Liu et al., Nuclear Fusion 64, 076007 (2024)

Mechanism 2: Reduction of zonal flows in the presence of ITG

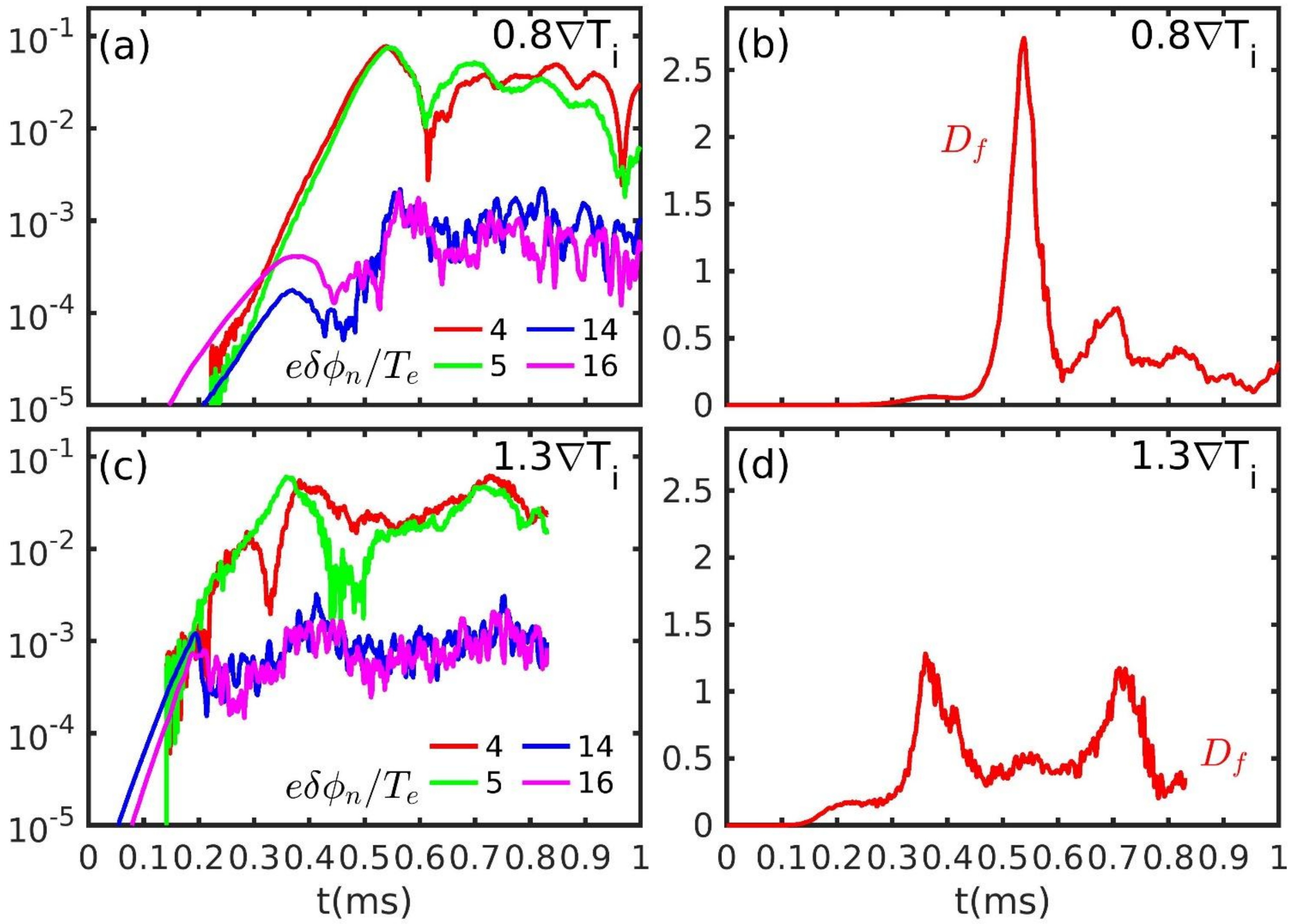
- ➤ Zonal flows generated by RSAE carried by thermal plasma
- ➤ ITG reduces amplitude of δn_{i00} and δn_{e00}, especially for low k_r component
- ➤ Longer wavelength zonal flows are more effective to suppress RSAE



- P. Liu et al., Nuclear Fusion 64, 076007 (2024)

Dependence of RSAE turbulence on ITG turbulence intensity

- Change ∇T_i to provide weaker or stronger background ITG
- Weaker ITG microturbulence leads to smaller EP transport
- Stronger ITG microturbulence leads to larger EP transport

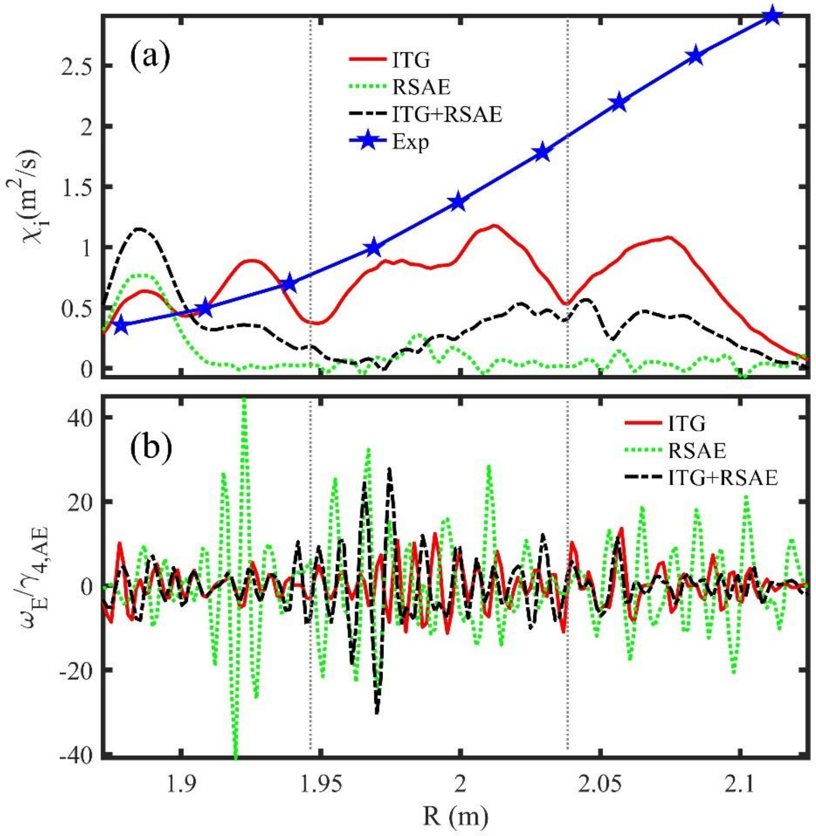


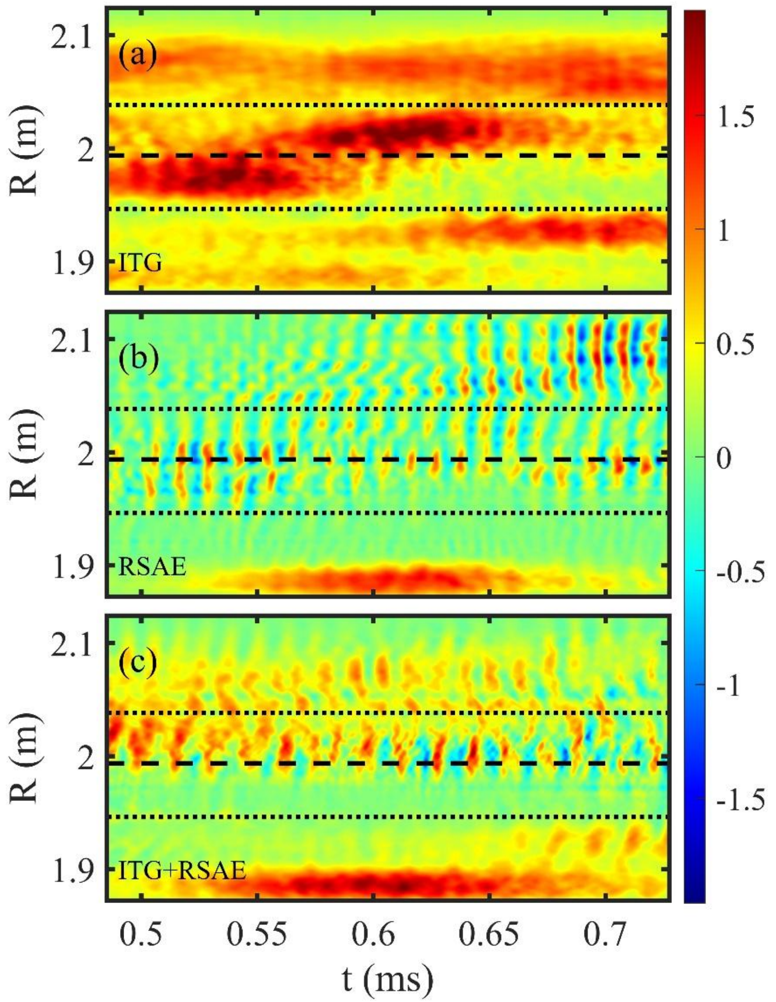
- P. Liu et al., Physical Review Letters 128, 185001(2022)

RSAE reduces thermal ion heat transport driven by ITG

- ➢ RSAE drive little thermal ion heat flux

- ➢ In simulation coupling ITG & RSAE
  - ❖ Thermal ion heat flux decreases and oscillates with RSAE frequency
  - ❖ Stronger zonal flows generated by RSAE near but inside q_{min} greatly reduce the thermal ion heat flux



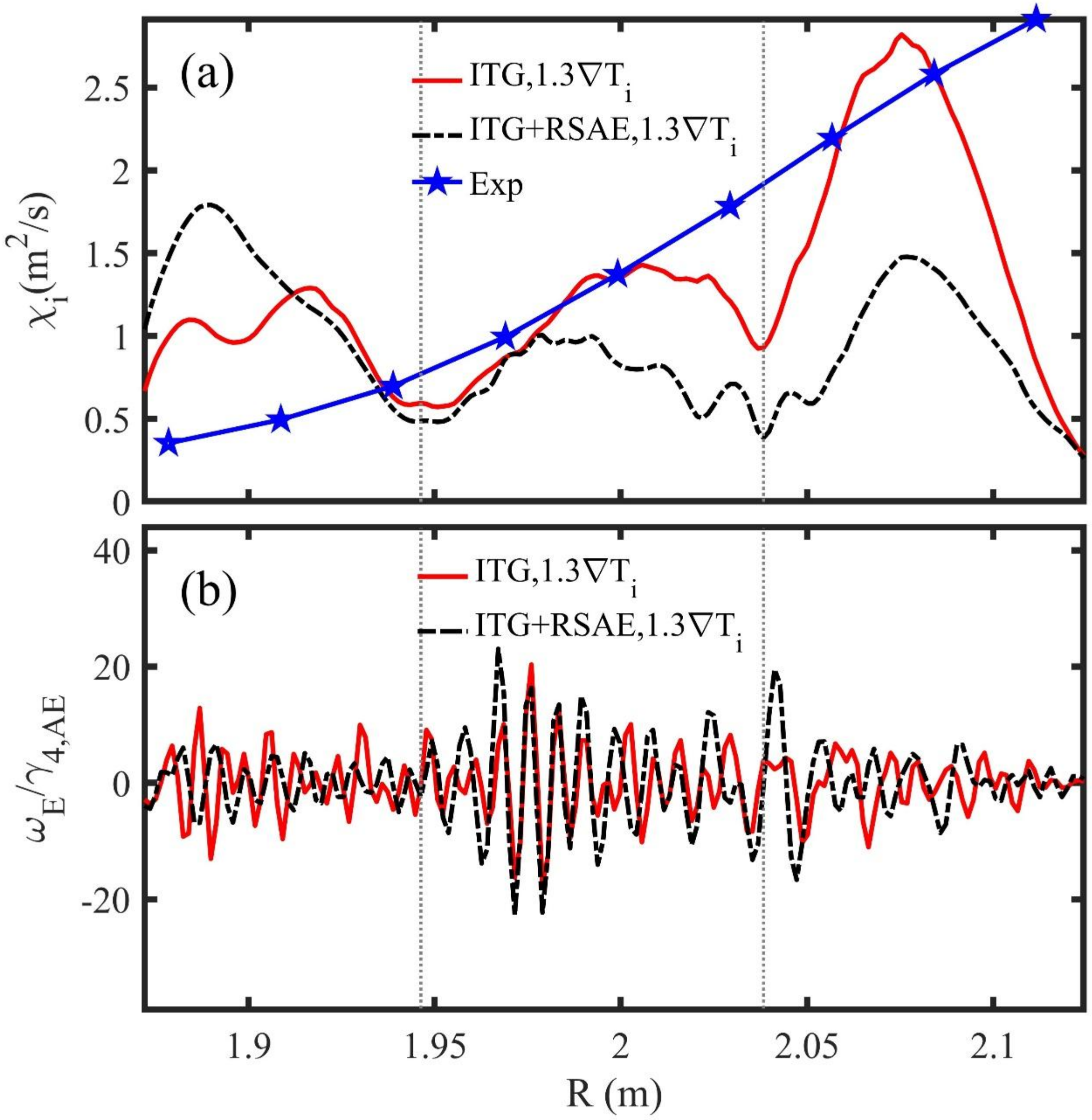


- P. Liu et al., Nuclear Fusion 64, 076007 (2024)

Effects of RSAE on stronger ITG are weaker

- Suppression of χ_i becomes weaker

- χ_i close to experimental measures



- P. Liu et al., Nuclear Fusion 64, 076007 (2024)

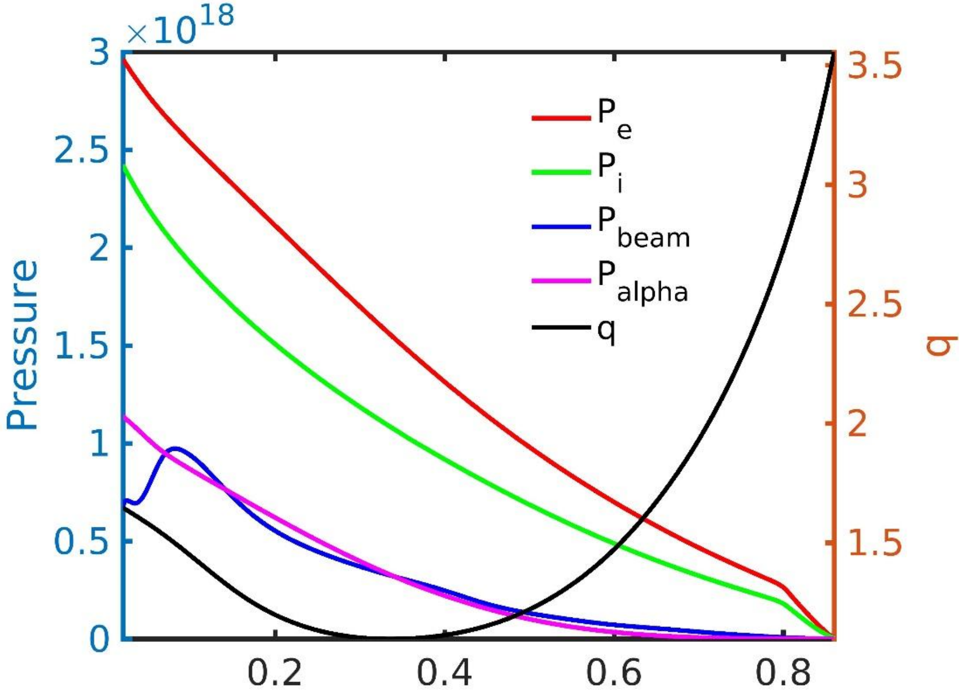
Outline

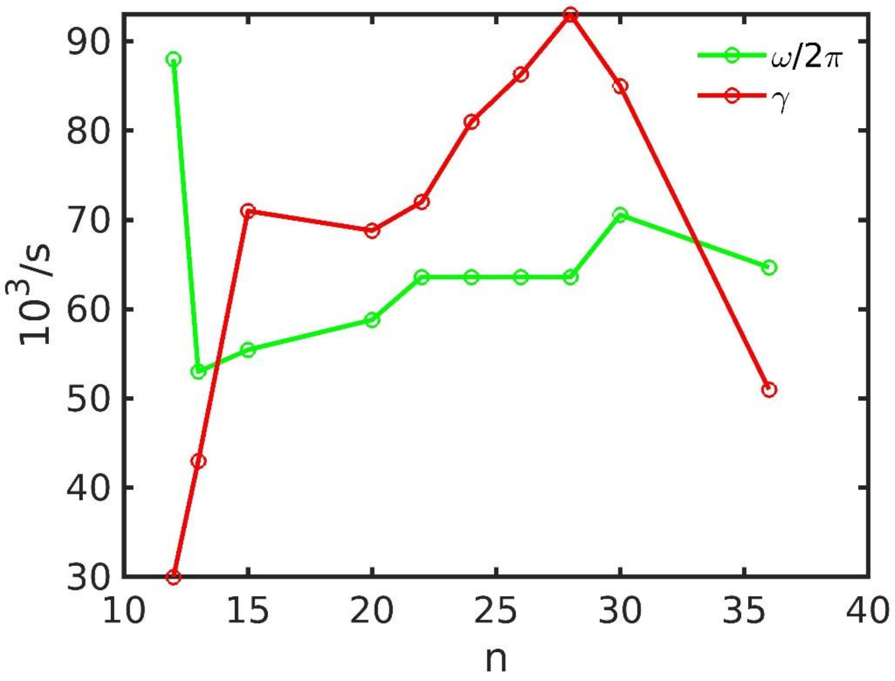
- Global simulations in ITER steady state scenario #131041--------Prediction of α particle confinement in burning plasmas

Equilibrium and linear dispersion

- Global GTC simulations include Beam ion (anisotropic slowing down) & α particle (isotropic slowing down).

- Strong unstable BAE/RSAE with $n = [15,30]$ near q_{min} flux surface.



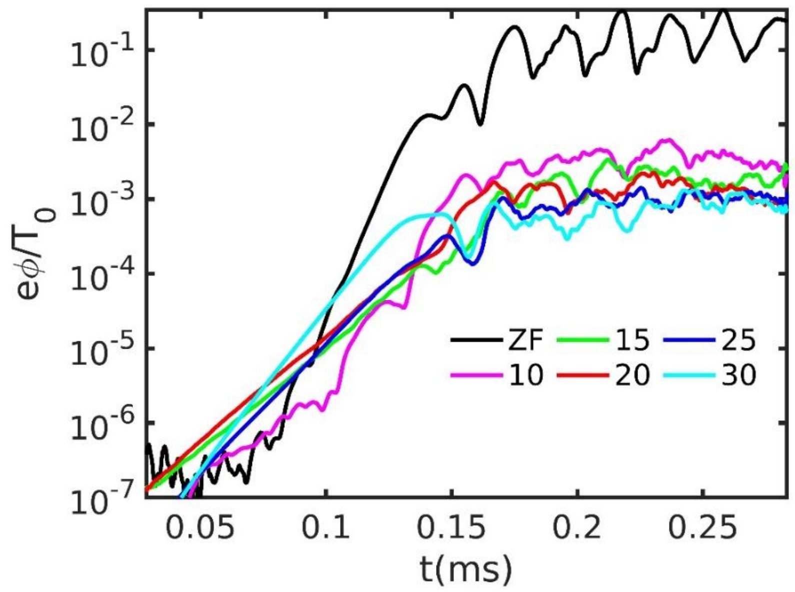


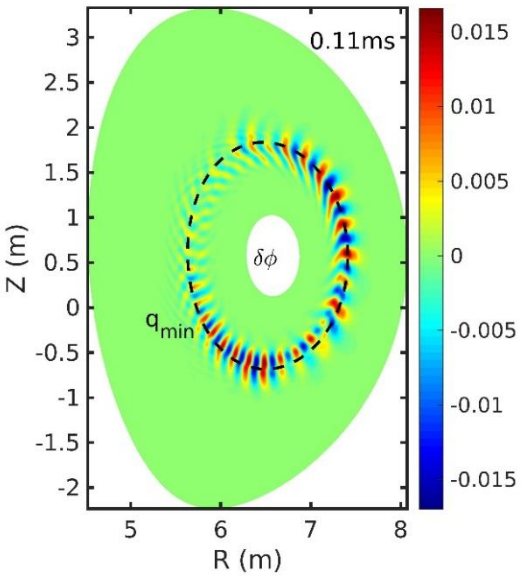
$$f_{BAE} = 59kHz$$

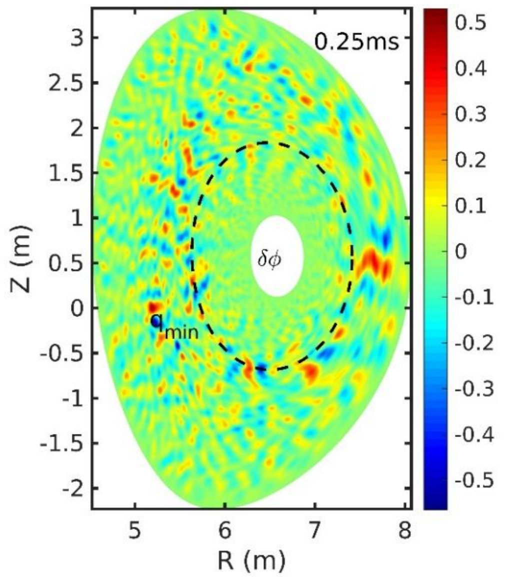
Quasi steady state AE turbulence in multiple AE ($n = [10, 30]$ & ZF)

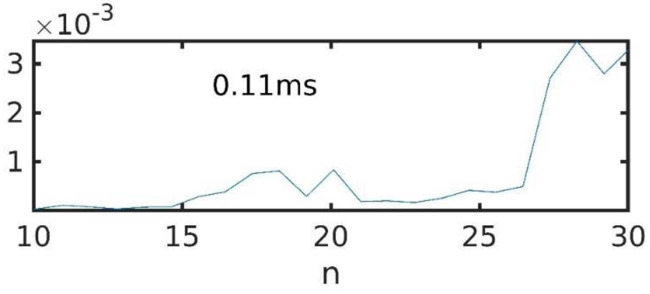
- Within $0.1 - 0.15ms$, linearly stable n=10,11 BAE nonlinearly generated with $\gamma_{10} \sim \gamma_{ZF} \sim 2\gamma_{30}$, and saturate at higher level.

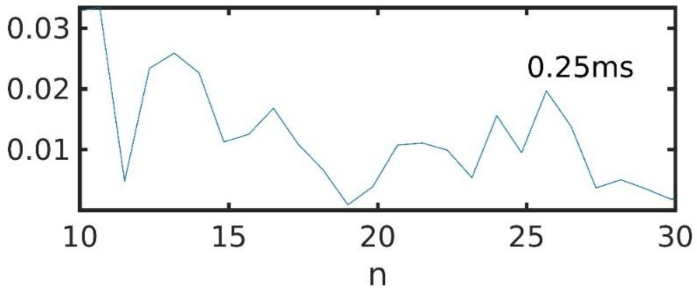
- Quasi steady state AE turbulence after nonlinear saturation.





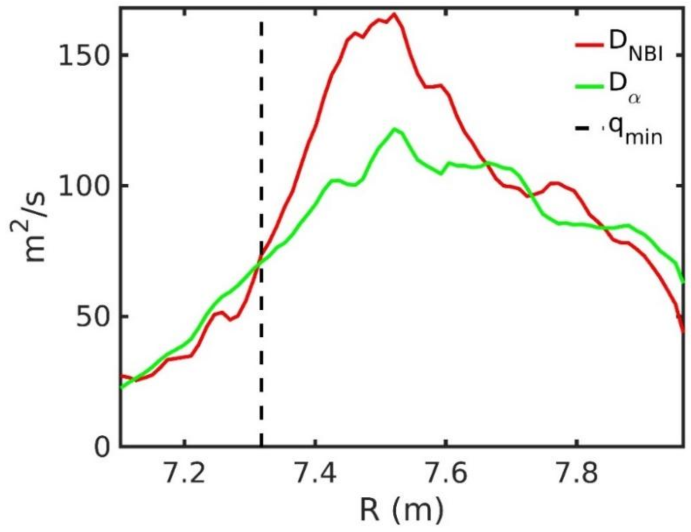


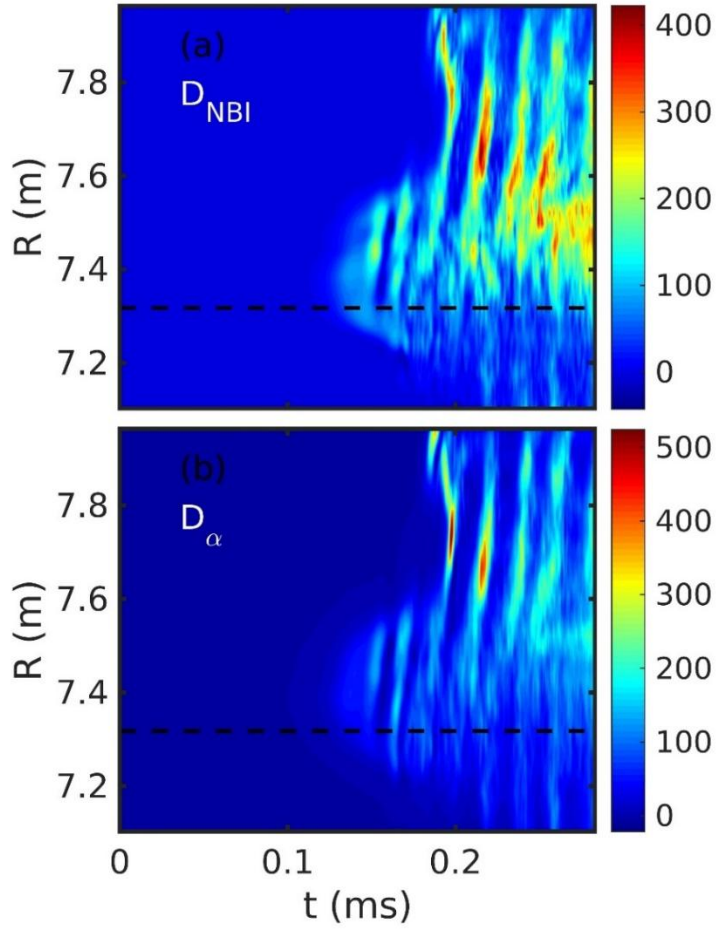




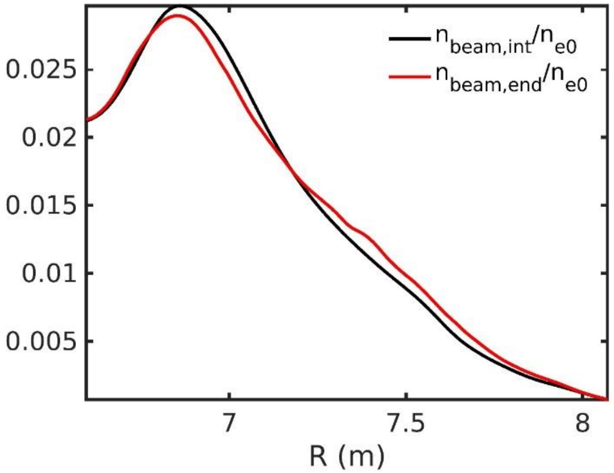
Huge EP transport driven by multiple n AE

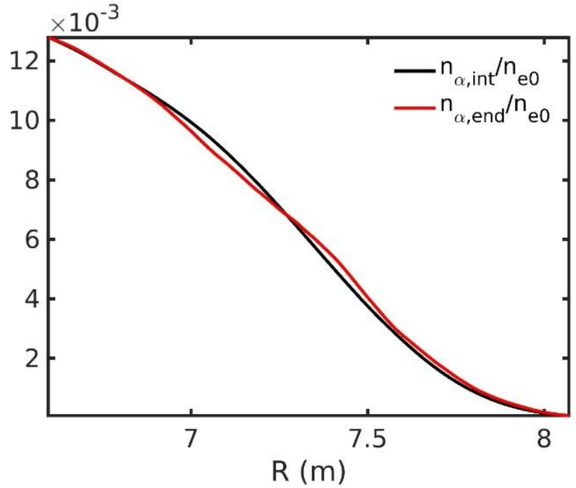
- Huge EP transport after $0.18ms$ in whole radial domain.
- AE turbulence and EP transport modulated by GAM/BAE after nonlinear saturation.





- Profile relaxation of beam ion & α particle within $0.14ms$. (Much smaller than the EP slowing down time)





Summary

- GK simulation in DIII-D.
  - Simulations focusing on AE only could not explain experimental observations.
  - Regulation of ITG microturbulence leads to quasi-steady state RSAE
  - RSAE modulates thermal ion heat flux driven by ITG
  - For a stronger background ITG, the regulation of the RSAE by the ITG is stronger, while the RSAE effects on the ITG are weaker
  - Qualitative agreement between GTC simulation and experimental measurements validates nonlinear physical model of GTC
- GK simulation in ITER steady state scenario.
  - Multiple strong unstable modes.
  - Quasi steady state AE turbulence & large EP transport in multiple AE.
  - Unrealistic α particle and NBI profiles in ITER SS?