SELF-ORGANIZED STATES OF ALFVÉN EIGENMODES AND ZONAL MODES VIA CROSS-SCALE INTERACTIONS

[1]Qinghao Yan, [2]P. H. Diamond

[1]Center for Fusion Sciences, Southwestern Institute of Physics, Chengdu, China
[2]Department of Astronomy and Astrophysics and Department of Physics, University of California San Diego, La Jolla, United States of America

Email: qinghaoyan@outlook.com

1. INTRODUCTION

Energetic particles (EPs) are known to drive instabilities in magnetically confined fusion plasmas, such as toroidal Alfvén eigenmodes (TAEs) and energetic particle modes (EPMs), which can significantly impact EP transport and affect plasma confinement [1]. Therefore, understanding the saturation mechanisms of EP-driven instabilities remains a key, long-standing challenge in fusion research. However, recent experimental results have revealed an intriguing phenomenon -- the formation of internal transport barriers (ITB) induced by energetic particles (EP) [2–6], where the underlying physical mechanisms remain unclear. Previous studies suggest that ITBs could be influenced by fast particle dilution[7, 8], electromagnetic stabilization [9] and zonal mode (ZM) stabilization [10–13]. Among these, ZM stabilization plays a dual role: saturating Alfvén eigenmodes (AE) and forming an ITB. While existing models describe how TAEs generate ZMs, they lack a self-consistent saturation mechanism [14–17]. This work introduces a novel cross-scale interaction model in which TAE-driven ZMs is damped by collisionless drag via geodesic acoustic transference (GAT) [18–21], leading to a new pathway for EP energy transfer to the thermal plasma, as shown in Fig 1.

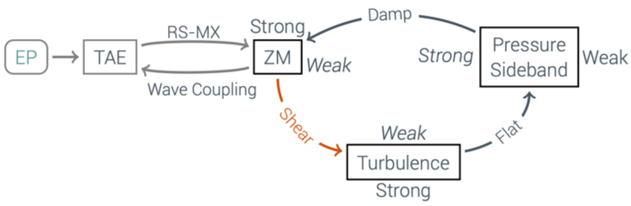

Fig 1. A feedback diagram for TAE and ZM with energy deposition from EP to thermals. The ZM saturates the TAE via wave coupling and suppresses drift wave (DW) turbulence via shearing effect, while the thermal plasma damps the ZM, resulting in heating of the thermal ions. Through ZM, EP/TAE physics and conventional DW turbulence physics are coupled.

2. KEY RESULTS

Our study develops a Predator-Prey type model for the coupled dynamics of EP, TAE, turbulence, and ZM, emphasizing the role of ZM damping in regulating TAE saturation. The key findings include:

- **TAE Saturation Mechanism:** In conventional models, Alfvén eigenmodes can be saturated via relaxation of the EP profile or velocity space gradients, driven by transport induced by the modes themselves. However, when the EP source is both strong and sustained, these conventional saturation mechanisms may be insufficient. We established the evolution model of TAE and ZM following Ref. [16, 17], where we clarified the relative magnitudes of the different driving sources for ZM and highlighted the energy-conserving interactions between TAE and ZM. With a sustained EP profile and strongly excited TAE, zonal modes are directly driven by TAE via Reynolds and Maxwell stresses, and are then damped through both collisional and collisionless drag. The evolution of TAE in the presence of ZMs conserves energy, thereby closing the system's feedback loop and forming a Predator-Prey type model [22]. Through this energy-conserved TAE-ZM interaction, TAE saturation is achieved, with the saturation level being controlled by the damping rate of the ZM. In core plasmas with low collisionality, ZM collisionless damping becomes the dominant process.
- **Geodesic Acoustic Transference (GAT) as a Damping Mechanism:** In a tokamak, the toroidal magnetic field decreases with increasing major radius, leading to the compressibility in the $E \times B$ flow along the poloidal direction. This compressibility generates a pressure sideband, which further

couples zonal flow (ZF) with ion flow and parallel current. This process is referred to as geodesic acoustic transference (GAT) [18–20], as shown in Fig 2. In the low-collisionality regime considered here, turbulent mixing of the pressure sideband serves as the primary dissipation mechanism. We identify GAT as a novel pathway for ZM collisionless damping, where ZM energy dissipates into the thermal plasma via turbulence mixing of the thermal pressure sideband. The effective collisionless damping rate of ZF from GAT process is $\hat{\nu}_G \propto \omega_{GAM}^2 \tau_{turb}/\omega_A$, which leads to the conclusion that the saturation level of TAE is linked to the intensity of thermal turbulence (characterized by τ_{turb}).

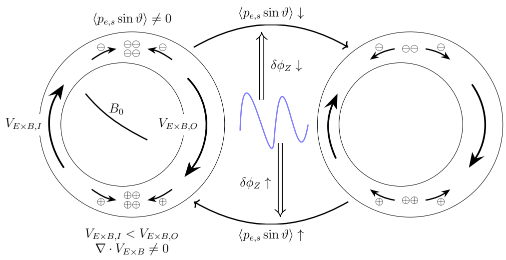

Fig 2. Illustration of geodesic acoustic transference (GAT). Due to the variation of the toroidal magnetic field, the $E \times B$ flow exhibits compressibility, leading to the generation of a pressure sideband. As a result, the zonal flow (ZF) couples with ion flow, parallel current, and the pressure sideband. In a low-collisionality regime, ZF energy is dissipated through turbulent mixing via the pressure sideband.

- **Alpha Channeling Effect:** The energy transferred through ZM collisionless damping leads to the heating of the thermal plasma, introducing a new "alpha channeling" mechanism. The heating power is proportional to the ZM collisionlless damping rate $\propto \hat{\nu}_G V_{E\times B}^2$, which can be distributed to both ions and electrons when temperature ratio $\tau_i \equiv T_i/T_e \sim 1$, or predominately into electrons when $\tau_i \ll 1$. This process may provide an effective means of distributing fusion-born alpha particle energy.
- **Suppression of ITG Turbulence:** The estimated zonal flow shearing in our model surpasses the typical linear growth rate of ITG modes, leading to ITG suppression and the possible formation of an ITB. The criterion for ITB formation is estimated as $\gamma_{TAE}/\gamma_{ITG} > k_{\theta,0}/k_Z$. The feedback process between TAE-driven zonal flows and thermal turbulence is incorporated into the TAE/ZM predator-prey model. Given that TAE saturation amplitude is linked to turbulence intensity, our model predicts a *seesaw-like* relationship between EP transport and thermal turbulent transport within some parameter regimes. Specifically, increased thermal turbulence indirectly reduces EP transport by modulating ZM collisionless damping, while higher TAE amplitude strengthens zonal flow shearing, thereby suppressing turbulent transport. We analyze the possible fix points of the system and investigate how the system evolves around these points.

3. CONCLUSION

Our findings provide a self-consistent explanation for EP-driven ITB formation through the interplay of TAEs, ZMs, and turbulence. Unlike traditional models where TAE saturation occurs via EP profile relaxation or wave trapping, our work reveals an alternative pathway by introducing ZM collisionless damping. This insight is crucial for understanding plasma confinement in future burning plasma. The results also highlight the importance of cross-scale interactions in fusion plasmas, demonstrating how meso-scale zonal structures can mediate energy transfer between fast particles and turbulence. This could impact transport modeling in fusion devices and provide new scenario for turbulence suppression via TAE-direct-driven zonal flows.

ACKNOWLEDGEMENTS

We thank Ruirui Ma, Michael Fitzgerald, T. S. Hahm, Gyungjin Choi, Xiaodi Du and Wei Chen for useful discussions. This work was supported by the National Key R&D Program of China under Grant No. 2022YFE03100004 and National Science Foundation of China Grant No.12175053, U.S. DOE, Office of Science, under Award Number DE-FG02-04ER54738. The authors would like to thank the Isaac Newton Institute for Mathematical Sciences, Cambridge, for support and hospitality during the Program "Anti-diffusive Dynamics: from Sub-Cellular to Astrophysical Scales", where part of the work on this paper was undertaken. This work was supported by EPSRC grant EP/R014604/1.

REFERENCES

[1] CHEN, L., ZONCA, F., Physics of Alfv\'en waves and energetic particles in burning plasmas, Rev. Mod. Phys. **88** 1 (2016) 015008.

[2] DI SIENA, A. et al., New high-confinement regime with fast ions in the core of fusion plasmas, Phys. Rev. Lett. **127** 2 (2021) 025002.

[3] HAN, H. et al., A sustained high-temperature fusion plasma regime facilitated by fast ions, Nature **609** 7926 (2022) 269.

[4] MAZZI, S. et al., Enhanced performance in fusion plasmas through turbulence suppression by megaelectronvolt ions, Nat. Phys. **18** 7 (2022) 776.

[5] CITRIN, J., MANTICA, P., Overview of tokamak turbulence stabilization by fast ions, Plasma Phys. Control. Fusion **65** 3 (2023) 033001.

[6] GARCIA, J. et al., Stable Deuterium-Tritium plasmas with improved confinement in the presence of energetic-ion instabilities, Nat. Commun. **15** 1 (2024) 7846.

[7] HAHM, T.S., CHOI, G.J., PARK, S.J., NA, Y.-S., Fast ion effects on zonal flow generation: A simple model, Phys. Plasmas **30** 7 (2023) 072501.

[8] CHOI, G.J., DIAMOND, P.H., HAHM, T.S., On how fast ions enhance the regulation of drift wave turbulence by zonal flows, Nucl. Fusion **64** 1 (2023) 016029.

[9] ROMANELLI, M., ZOCCO, A., CRISANTI, F., CONTRIBUTORS, J.-E., Fast ion stabilization of the ion temperature gradient driven modes in the Joint European Torus hybrid-scenario plasmas: a trigger mechanism for internal transport barrier formation, Plasma Phys. Control. Fusion **52** 4 (2010) 045007.

[10] ZHANG, H., LIN, Z., Nonlinear Generation of Zonal Fields by the Beta-Induced Alfvén Eigenmode in Tokamak, Plasma Sci. Technol. **15** 10 (2013) 969.

[11] SPONG, D.A. et al., Nonlinear dynamics and transport driven by energetic particle instabilities using a gyro-Landau closure model *, Nucl. Fusion **61** 11 (2021) 116061.

[12] MAZZI, S. et al., Gyrokinetic study of transport suppression in JET plasmas with MeV-ions and toroidal Alfvén eigenmodes, Plasma Phys. Control. Fusion **64** 11 (2022) 114001.

[13] DI SIENA, A. et al., Electromagnetic turbulence suppression by energetic particle driven modes, Nucl. Fusion **59** 12 (2019) 124001.

[14] CHEN, L., ZONCA, F., Nonlinear Excitations of Zonal Structures by Toroidal Alfv\'en Eigenmodes, Phys. Rev. Lett. **109** 14 (2012) 145002.

[15] QIU, Z., CHEN, L., ZONCA, F., Gyrokinetic theory of toroidal Alfvén eigenmode saturation via nonlinear wave–wave coupling, Rev. Mod. Plasma Phys. **7** 1 (2023) 28.

[16] QIU, Z., CHEN, L., ZONCA, F., Effects of energetic particles on zonal flow generation by toroidal Alfvén eigenmode, Phys. Plasmas **23** 9 (2016) 090702.

[17] QIU, Z., CHEN, L., ZONCA, F., Nonlinear excitation of finite-radial-scale zonal structures by toroidal Alfvén eigenmode, Nucl. Fusion **57** 5 (2017) 056017.

[18] SCOTT, B., Energetics of the interaction between electromagnetic ExB turbulence and zonal flows, New J. Phys. **7** (2005) 92.

[19] SCOTT, B., The geodesic transfer effect on zonal flows in tokamak edge turbulence, Phys. Lett. A **320** 1 (2003) 53.

[20] SCOTT, B., Three-dimensional computation of drift Alfvén turbulence, Plasma Phys. Control. Fusion **39** 10 (1997) 1635.

[21] YAN, Q., DIAMOND, P.H., AE-Driven Zonal Modes Produce Transport Barriers and Heat Thermal Ions by Cross-Scale Interactions, submitted to Nuclear Fusion (2025).

[22] DIAMOND, P.H., KIM, Y. -B., Theory of mean poloidal flow generation by turbulence, Phys. Fluids B Plasma Phys. **3** 7 (1991) 1626.