9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

The role of kinetic Alfvén waves in burning plasma self-organization*

Fulvio Zonca[1,2], Liu Chen[2,1], Matteo V. Falessi[1] and Zhiyong Qiu[3,1],
[1]Center for Nonlinear Plasma Science and ENEA C.R. Frascati, 00044 Frascati, Italy,
[2]Institute for Fusion Theory and Simulation, School of Physics,
Zhejiang University, Hangzhou 310027, China,
[3]Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), Hefei 230031, China
e-mail: fulvio.zonca@enea.it

That burning plasma are complex self-organized systems is widely recognized [1,2,3], yet it poses extremely challenging questions to actually addressing the fundamental physics underlying their behaviors and, ultimately, to developing a reliable predictive capability of reactor relevant plasma operation and performance. In order to properly describe the slowly evolving nonlinear equilibria characterizing self-organized burning plasmas, one needs to lift transport description to the phase space [4,5,6], thereby capturing deviations from local thermodynamic equilibrium. The zonal state represents a portrait of nonlinearly evolving magnetized tokamak plasmas [4,5]. It consists of (i) phase space zonal structures (PSZS) [1,3]; which are undamped by fast collisionless processes and reflect the meso- and macro-scale toroidally symmetric particle distributions, (ii) their fast-varying spatiotemporal counterpart, (iii) zonal electromagnetic fields (ZFs) [5], and (iv) a finite level of toroidal symmetry breaking fluctuations. Meanwhile, behavior of burning plasmas inevitably reflects the properties of the Alfvénic state [7,8]; i.e., it exhibits properties of large shear Alfvén waves [9] that can exist for long times without being broken by nonlinear processes [10]. This is also intimately connected with the natural excitation of short wavelength kinetic Alfvén waves (KAW) [11] by mode conversion, which renders the behavior of burning plasmas intrinsically global [2]. The properties of Alfvénic state, of shear Alvén waves and their short wavelength counterpart, KAWs, also impact the zonal state, in particular the ability of generating ZFs. In this work, the self-consistent evolution of the zonal state will be analyzed in the presence of KAW excited nonlinearly in the self-consistent plasma evolution. We will show that these processes are important with or without a population of energetic particles (EP) dominating the plasma response. In particular, we will report about results obtained with GTC [12] and ORB5 [13] nonlinear gyrokinetic codes. We will also illustrate the predictive capability of the phase space transport code ATEP [14], with emphasis on the EP transport by toroidal Alfvén eigenmodes (TAE) in the ITER 15 MA case.

References

[1] F. Zonca et al., New J. Phys. **17**, 013052 (2015).
[2] F. Zonca et al., Plasma Phys. Control. Fusion **57**, 014024 (2015).
[3] L. Chen and F. Zonca, Rev. Mod. Phys. **88**, 015008 (2016).
[4] M. V. Falessi and F. Zonca, Phys. Plasmas **26**, 022305 (2019).
[5] F. Zonca, L. Chen, M. V. Falessi and Z. Qiu, J. Phys.: Conf. Ser. **1785**, 012005 (2021).
[6] M. V. Falessi, L. Chen, Z. Qiu and F. Zonca, New J. Phys. **25**, 123035 (2023).
[7] C. Walén, Ark. Mat. Astron. Fys. 30A, 1 (1944).
[8] H. Alfvén, *Cosmical Electrodynamics* (Clarendon, Oxford, United Kingdom, 1950)
[9] H. Alfvén, Nature **150**, 405 (1942).
[10] L. Chen and F. Zonca, Phys. Plasmas **20**, 055402 (2013).
[11] H. Hasegawa and L. Chen, Phys. Fluids **19**, 1924 (1976).
[12] L. Chen et al., Nucl. Fusion **65**, 016018 (2025).
[13] A. Bottino et al., J. Phys.: Conf. Ser. **2397**, 012019 (2023).
[14] P. Lauber et al., Nucl. Fusion 64, 096010 (2024).

*Acknowlegments: 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; Projects No. ENR-MOD.01.MPG and AC-TSVV.10.MPG). 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. This work was also supported by the National Science Foundation of China Project No. 12261131622 and by the Italian Ministry for Foreign Affairs and International Cooperation Project No. CN23GR02.