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

Electromagnetic simulations of Toroidal Alfvén Eigenmode (TAE) using GYSELA

S. Raj[1], Y. W. Cho[1], Z. S. Qu[1], G. Brochard[3], L. Bramucci[2], P. Donnel[3], R. Bigué[3], S. Mazzi[3], G. Dif-Pradalier[3], D. Zarzoso[4], K. Obrejan[3], V. Grandgirard[3], K. Lim[1], R. Varennes[1], X. Garbet[1]

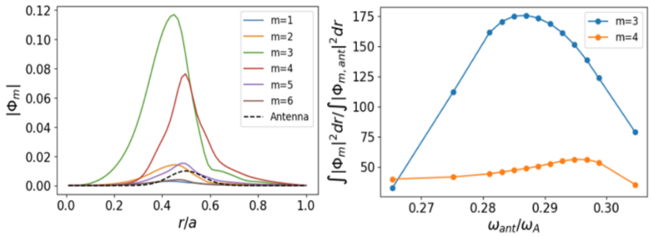
[1] *School of Physical and Mathematical Sciences, Nanyang Technological University, 637371 Singapore,* [2]*Consorzio RFX, Padova, Italy,* [3]*IRFM, CEA Cadarache, France,* [4]*Aix Marseille University, CNRS, Centrale Med, M2P2, Marseille, France*

e-mail (speaker): shrish.raj@ntu.edu.sg

Toroidal Alfvén Eigenmodes (TAEs) are key instabilities in magnetically confined plasmas, due to their interaction with energetic particles and background turbulence [1]. By enhancing energetic ion transport, they could degrade confinement in future devices like ITER [2,3]. While their excitation mechanisms are relatively well understood, their nonlinear saturation —especially the role of zonal flows — remains elusive. Furthermore, nonlinear interactions between TAEs and drift-wave microturbulence are not well understood. Some experimental evidence suggests that TAEs may even mitigate turbulence. The understanding of these processes requires global, full-F, flux-driven simulations, as numerous global gyrokinetic studies of TAEs have been performed, but to our knowledge, none have yet used a full-F, flux-driven framework. This approach can unveil unforeseen effects during the nonlinear evolution of TAE modes.

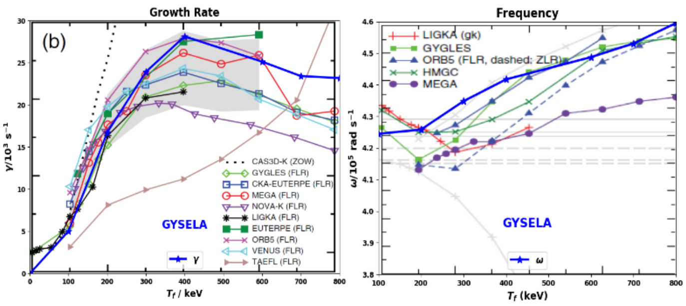
In this study, we present simulations of both antenna-driven and fast ion-driven TAEs using the GYrokinetic SEmi-LAgrangian (GYSELA) code, a global, flux-driven, full-F, semi-Lagrangian framework designed for nonlinear gyrokinetic simulations of plasma turbulence in tokamaks [4]. To investigate the linear excitation and evolution of TAEs, we have solved the electromagnetic gyrokinetic equations. A mixed-variable scheme has been implemented to solve the Ampère equation [5]. This helps in reducing the numerical inaccuracies associated with the parallel vector potential.

The simulation results demonstrate consistent and accurate modeling of both antenna-driven and energetic particle (EP) driven TAEs, with trends that closely align with previously reported ITPA benchmark studies in [6,7]. In the antenna-driven scenarios, resonant excitation of $m = 3$ and $m = 4$ modes for $n = 2$ TAEs near $r/a \approx 0.5$ with sharp frequency response peak at $\omega_{ant}/\omega_A \approx 0.287$, confirm precise matching with TAE eigenfrequencies as shown in Fig.1(a)-(b). This further validates GYSELA's capability to accurately capture both the radial localization and symmetry of the modes. In EP-driven scenarios, GYSELA accurately reproduces the expected growth rate and frequency scaling with fast-ion temperature (T_f), showing close agreement with other codes, as illustrated in Fig. 2(a)-(b). Phase-space diagnostics based on energy and canonical toroidal momentum reveal multiple resonances in both linear and nonlinear phases, offering insights into EP-driven mode saturation. A potential signature of zonal flows appears in the radial electric field evolution, likely driven nonlinearly by antenna-excited TAEs, indicating self-generated shear layers critical for regulating turbulence and saturation. Recent works [8,9] further emphasize the pivotal role of zonal flows in the nonlinear saturation of EP-driven modes.



(a) (b)

Fig.1: (a) Radial profile of electrostatic plasma potential for $n = 2$ TAE mode. The radial profile of antenna potential is depicted in black-dashed curve. (b) Linear excitation of $n = 2$ TAE at arrange of frequencies near the resonance. The amplitude of plasma potential is integrated in the radial direction and its maximum over a time span is taken.



(a) (b)

Fig.2: (a) Growth rate of the TAE mode as a function of T_f for the ITPA case. (b) Corresponding TAE frequency variation with T_f showing strong agreement with other established codes.

References:

[1] Cheng, C. Z., et.al. *Annals of Physics* 161.1 (1985): 21-47.
[2] Heidbrink, W. W. *Physics of Plasmas* 15.5 (2008).
[3] Mazzi, S. *et al*, *Nature Physics* **18** 776 (2022).
[4] Grandgirard. V, et al. *Computer physics communications* 207 (2016): 35-68.
[5] Mishchenko, A. *et al. Physics of Plasmas* **24** 081206 (2017).
[6] Sadr, M. *et al. Plasma Physics and Controlled Fusion* **64** 085010 (2022).
[7] Könies, A. *et al. Nucl. Fusion* **58** 126027 (2018).
[8] Todo, Y. *et.al. Nuclear Fusion*, **52**(3), 033003 (2012).
[9] Brochard, Guillaume, *et al. Physical Review Letters* 132.7 (2024): 07510