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Electromagnetic turbulence simulations in edge plasma with the SOLEDGE3X code

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This contribution presents a new electromagnetic turbulence model implemented within the drift-reduced fluid code SOLEDGE3X[1], designed for first-principle edge plasma simulations in realistic tokamak geometries. These developments extend the capabilities of SOLEDGE3X[2], which relied thus far on an electrostatic assumption for the non-adiabatic electron response to fluctuations, to conditions where electromagnetic effects and electron inertia become non-negligible. Previous work indicates that such conditions might already be attained in low-β regions such as the edge and scrape-off-layer[3].

The new model consists of three main extensions to the original framework: (i) magnetic induction, via the time derivative of the parallel vector potential $A_\parallel$ in Ohm's law; (ii) magnetic flutter, which introduces nonlinear fluctuations of the magnetic field; and (iii) finite electron mass, accounting for an electron inertia term in Ohm's law. These effects are incorporated using a conservative second-order finite volume scheme and a semi-implicit time-stepping algorithm. A toroidally and poloidally staggered grid is introduced to discretize $A_\parallel$ and $j_\parallel$, which allows a consistent evaluation of parallel derivatives while preserving the structure of the vorticity and current operators. The additional computational complexity introduced by these terms, in particular the doubling in size of the implicity-solved vorticity matrix, is addressed by a careful reformulation of the coupled system. In particular the finite electron mass acts as an effective lower bound on the parallel resistivity $\eta_\parallel$, thereby improving numerical conditioning in regions with low collisionality.

The model has been verified through the Method of Manufactured Solutions and benchmarked against linear theory, successfully recovering the expected transition from Alfvén to electron thermal wave regimes as the perpendicular wavenumber increases. Nonlinear simulations of blob dynamics and drift-wave instabilities in slab geometry reproduce known behaviors and validate the model's physical fidelity.

In a second step, we aim to compare the electrostatic and the full electromagnetic models in simulations on a diverted configuration inspired by the TCV-X21 benchmark scenario[4]. In both cases, a constant heat source is imposed on electrons and ions at the core boundary and fluid neutrals regulate the particle source to match a target density at the separatrix via a feedback scheme. From the benchmark case, the input heat flux is successively increased to evaluate transport properties and the evolution of profiles.

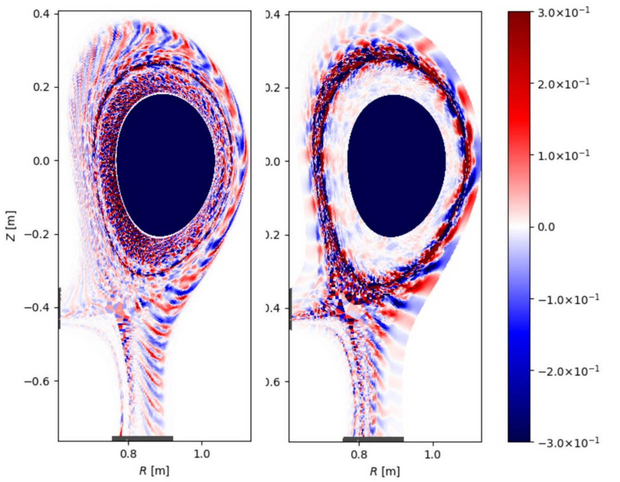

*Figure 1: relative fluctuations of the potential Φ with the electrostatic (**left**) and electromagnetic models (**right**)*

Magnetic induction and electron inertia lead to an increase of radial transport, with filamentary structures penetrating deeper into the SOL with larger blobs and accelerating the saturation of the temperature profile. Conversely, magnetic flutter exerts a stabilizing effect on drift-wave instabilities particularly pronounced in the core region, reducing turbulence intensity and steepening radial gradients, thereby improving local confinement.

References:

[1] Bufferand, H., et al. "Implementation of drift velocities and currents in SOLEDGE2D–EIRENE." *Nuclear Materials and Energy* 12 (2017): 852-857.
[2] Düll, R., et al. "An electromagnetic model in SOLEDGE3X for edge plasma turbulence simulations in tokamaks." *Journal of Computational Physics* (2025): 114052.
[3] Scott, B. "Three-dimensional computation of drift Alfvén turbulence." *Plasma Physics and Controlled Fusion* 39.10 (1997): 1635.
[4] Oliveira, D. S., et al. "Validation of edge turbulence codes against the TCV-X21 diverted L-mode reference case." *Nuclear Fusion* 62.9 (2022): 096001.