Non-Linear 3D Hybrid Kinetic-MHD Simulations of Alfvén Eigenmodes in the ASDEX Upgrade Tokamak

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INTRODUCTION

For a successful operation of future fusion reactors, fast-ions produced by auxiliary heating systems and fusion-born alpha particles need to be confined for a sufficient time to thermalize thus, transferring their energy to the bulk plasma. Alfvénic waves propagating along magnetic field lines can resonate with these energetic particles (EP) deflecting its trajectories, which is translated into a radial particle transport or eventually losses [1]. During the last decade, the international community has been pursuing the development of actuators to mitigate/suppress these Alfvénic instabilities [2]. Recent experiments on the ASDEX Upgrade (AUG) tokamak, have shown that externally applied 3D fields may be used to control Toroidally Induced Alfvén Eigenmodes (TAEs) in beam heated discharges with elevated q-profile and low collisionality [3]. TAEs have been fully suppressed in discharges with n = 2 3D fields by varying their poloidal spectrum (figure 1). Aiming to provide more insight about this actuator, the non-linear 3D hybrid kinetic-magnetohydrodynamic (MHD) MEGA code [4] has been upgraded to include externally applied 3D fields and is used to reproduce these experiments. Furthermore, a 2D wall for numerical particles is employed which will allow a synthetic signal of the recently installed suite of five fast-ion loss detectors (FILDs) in AUG [5,6,7].

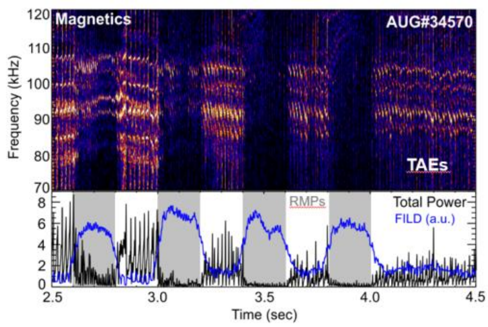

Fig.1. Overview of TAE suppression experiments in AUG.

a)A. Kallenbach *et al.*, Nucl. Fusion **53**, 102015 (2017)
b)H. Meyer *et al.*, Nucl. Fusion **57**, 102014 (2017)

SIMULATION MODEL AND INPUTS

The experimental observations presented here have been modelled with the non-linear 3D hybrid kinetic-MHD MEGA code, which has the capability of computing the bulk plasma and fast-ion dynamics self-consistently. In this code, the bulk plasma is described by the nonlinear MHD equations and the fast-ions are simulated with the gyrokinetic particle-in-cell (PIC) method. The extended Hazeltine-Meiss model [8] used in these simulations includes resistivity, thermal ion diamagnetic drift and equilibrium toroidal flow. Both delta-*f* and full-*f* methods [9] are available to apply the PIC algorithm to guiding-center markers. The electromagnetic fluctuations are averaged over the fast-ion gyro-orbit to account for finite Larmor radius effects (FLR). The equations of motion of each computational marker are solved using a fourth-order Runge-Kutta method, while the MHD equations are solved using a finite difference scheme. The interaction between fast-ions and the bulk plasma is considered by means of including the fast-ion current density in the MHD momentum equation. The fast ion current density results from the parallel velocity, the curvature and gradient drifts, and magnetization current.

The MHD equations are solved using a cylindrical grid of (128, 64, 256) points for (R, φ, z) coordinates respectively, covering the entire toroidal geometry and adjusting to the equilibrium last closed flux surface. The fits to the measured electron temperature and density profiles (see figure 2) are remapped onto the cylindrical grid and are used as the initial condition of these simulations. Using the Electron Cyclotron Emission (ECE) diagnostic, a (3,1) Double Tearing Mode (DTM) has been identified between $\rho_{pol} = 0.4$ and $\rho_{pol} = 0.6$. This mode flattens the equilibrium toroidal flow profile used in the Hazeltine-Meiss model. Additionally, the DTM is used as a q-profile constraint in the magnetic equilibrium reconstruction of the CLISTE [10] and IDE [11] codes, showing similar results. High spatial resolution CLISTE equilibrium reconstruction is used for these simulations.

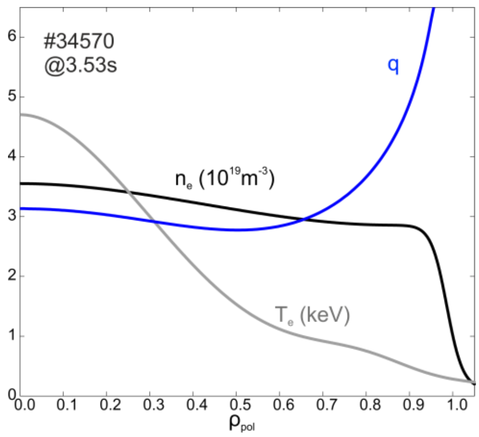

Fig.2. Fits to the measured profiles of equilibrium electron density (n_e) and electron temperature (T_e). Safety factor (q) taken from the magnetic equilibrium reconstruction.

4.2 million of delta-*f* markers describe an on-axis anisotropic beam slowing down distribution centred at normalized pitch-angle $\Lambda \equiv \mu B_0/E = 0.6$, with magnetic moment μ, particle energy E and magnetic field on axis B_0. The maximum velocity of this distribution corresponds to the beam energy of 93keV of the neutral beam injection (NBI) box at AUG.

SIMULATION RESULTS

A: Axisymmetric equilibrium

The MEGA simulations described in the previous section reproduce some of the key aspects of the experiments, such as the dominant *n* numbers, frequency and location of TAEs. Figure 3a) shows the evolution of the total energy associated to each toroidal mode number in a multimode simulation. The toroidal modes *n* = 3, 4 and 5 dominate the linear growth phase, agreeing with the experimental observations. Figure 3b)-d) depicts synthetic spectrograms of these dominant *n* numbers being just ~10kHz below the measured frequencies, which could be corrected by fine tuning the input kinetic profiles within their error bars. Figure 3e)-g) shows the poloidal structure of the radial velocity perturbation. The mode locations (ρ_{pol} = 0.6-0.8) agree with the measurements based on the cross-correlation between ECE and Mirnov coil diagnostics.

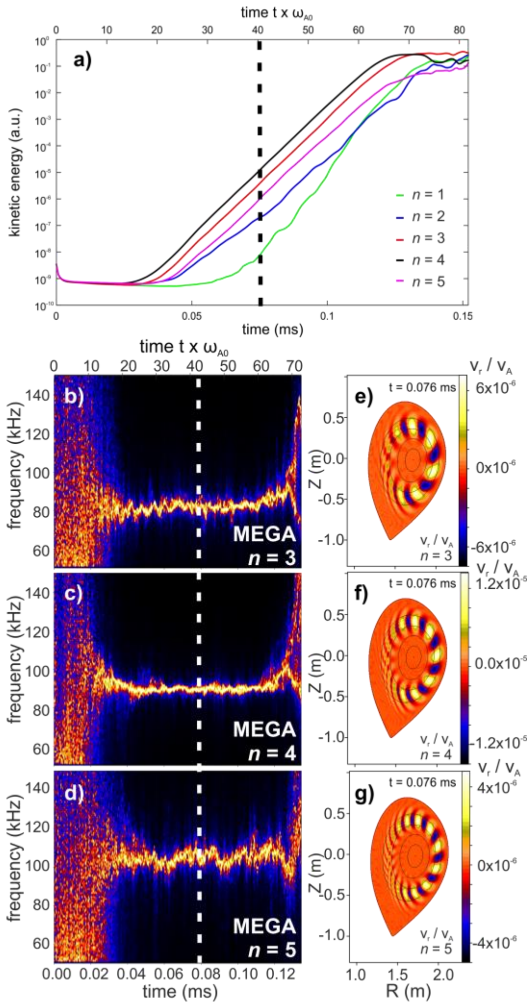

Fig. 3. For each toroidal mode number (a) energy evolution (b-d) synthetic spectrogram. (e-g) poloidal structure of radial velocity perturbation.

B: TAEs under externally applied 3D fields

The main toroidal components (*n* = 2 and *n* = 6) of the externally applied 3D fields produced by the ELM mitigation coils are added to the initial equilibrium while maintaining the magnetic divergency unaltered. To study their impact on Alfvénic activity, two identical simulations are performed changing only the poloidal spectrum of the 3D fields. Figure 4a) and b) shows that *n* = 4 #34570 simulation does not suffer a coherent frequency while #34571 does. Furthermore,

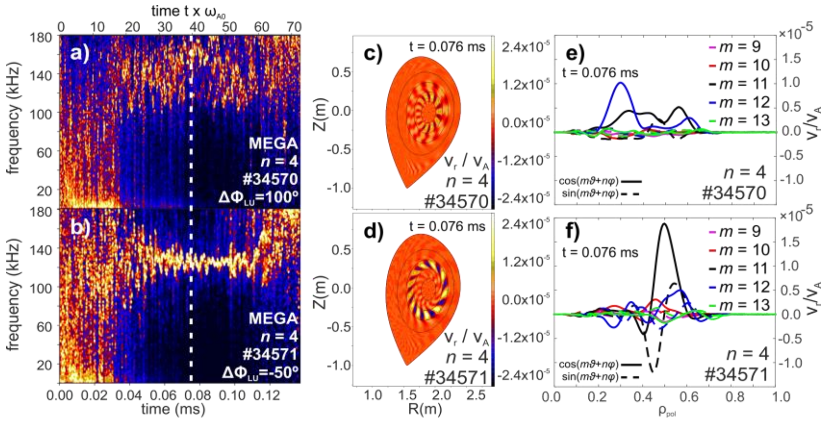

Fig. 4. Comparison of synthetic spectrograms (a-b) and poloidal structure (c-d) of Alfvénic activity for #34570 and #34571 externally applied 3D fields.

during the linear growth phase, the perturbation amplitude of #34570 is half of the calculated for #34571 (figure 4c-f), in agreement with the observed trend of TAE suppression/excitation experiments.

C: Implementation of a 2D wall including a synthetic FILD poloidal array in MEGA

An array of synthetic Fast-Ion Loss Detectors (FILD) has been included in MEGA by implementing a 2D wall for numerical particles. This wall deactivates and stores the information of the markers reaching the wall region. This new feature has a negligible computational cost (less than 0.2%). Nevertheless, it requires to expand the simulation domain so that the numerical particles can reach the main plasma facing components. Figure 5 depicts the angular distribution of fast-ion losses induced by MHD activity and externally applied 3D fields. The lower and upper divertor, the FILD systems and ELM mitigation coils are highlighted in white for easier visualization. An n = 2 pattern caused by 3D fields is observed just above the lower set of ELM mitigation coils. A study of MHD induced fast-ion losses using this new tool is ongoing. Figure 6 shows the synthetic signal of the recently installed FILD4 and FILD5 for the same discharge. It is noted that #34570 poloidal spectrum produces slightly more losses than #34571 for several simulations (different beams using both delta-*f* and full-*f* methods) agreeing with TAE suppression/excitation experiments.

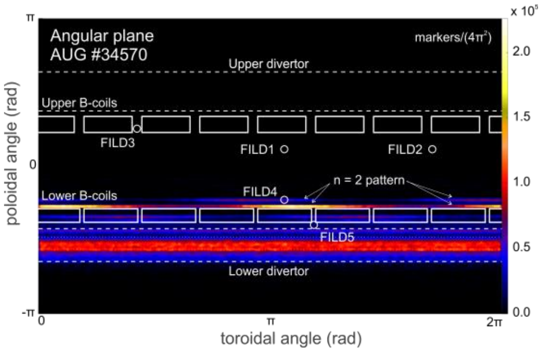

Fig. 5. Angular plane of marker losses on the vessel

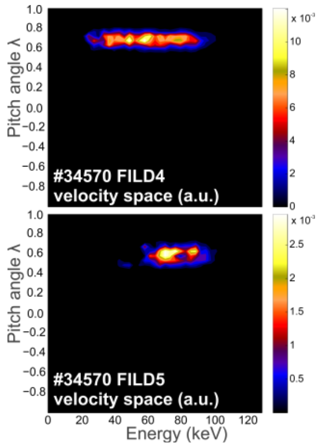

Fig. 6. Synthetic signal of the recently installed FILD4 and FILD5.

The hybrid kinetic-MHD code MEGA is used to simulate TAE suppression/excitation experiments in AUG including externally applied 3D fields and a synthetic FILD array.

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