Fluid models for burning and 3D plasmas: complementing the kinetic paradigm

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We highlight recent ANU-led research in energetic particle physics and multi-relaxed region MHD. Topics include (1) the inclusion of anisotropy and flow into tokamak equilibria, stability and wave-particle interaction studies[1,2] , (2) the calculation of energetic geodesic acoustic modes (EGAMs) using fluid theory[3], (3) the development and implementation of continuum damping in 3D[4], (4) the application of these tools to KSTAR, MAST and DIIID discharges, and (5) the ongoing development of multiple relaxed region MHD[5]. A common feature of the approaches adopted is the use of fluid theory to capture the physics of energetic particles and fully 3D fields.

Recently, equilibrium models and reconstruction codes have been generalised to include physics of anisotropy and toroidal flow[1]. These codes have been used to explore the impact on the magnetic configuration in regimes with large neutral beam heating, as well as determine the impact on particular discharges. In parallel to these developments, a single adiabatic extension of an MHD stability model that captures anisotropy and flow has been developed[2], and together with CGL models, implemented into the ideal MHD stability code MISHKA-ATF[6]. Figure 1 illustrates the difference in field configuration (q profile) and n=1 shear Alfven continuum and wave structure with and without anisotropy, for MAST discharge #29221, for which the beam plus thermal population gives $p_{||} / p_{\perp} \approx 1.7$. We have demonstrated that for toroidal Alfven eigenmodes, the differences in mode structure due to anisotropy is largely due to the change in configuration.

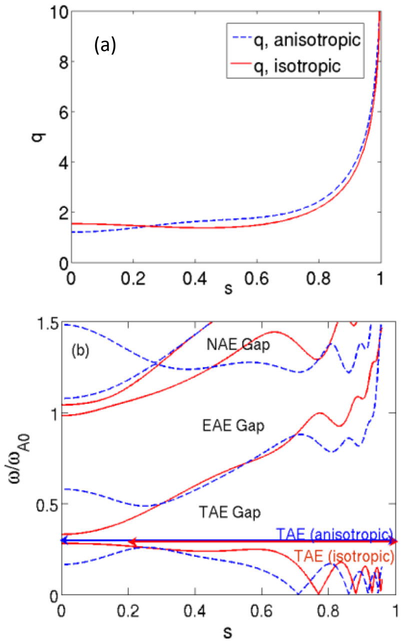

Fig. 1: (a) q profile of #29221, reconstructed with/ without anisotropy (b) shows the n=1 MHD continuum for the anisotropic (dashed) and isotropic (solid) cases. Solid horizontal lines are the TAEs and their radial localisation.

EGAMs are axisymmetric energetic particle modes found in toroidally confined plasmas resulting from the geodesic curvature of magnetic field lines. They are experimentally observed at half of the conventional GAM frequency and are localized at the core, where there is a significant fast particle population. Until recently, it was widely believed that EGAMs are driven unstable by a positive gradient of the fast particles in the velocity space. However, unlike previous studies which treat fast ions kinetically, we consider the thermal ions and fast ions as different type of fluids with a super thermal flow speed for the latter.[3] Surprisingly, as shown in Fig. 2, the frequency and growth rate predicted by our fluid mode agree well with the kinetic theory when the fast ion energy width is small, despite the absence of inverse Landau damping in the fluid model. This indicates the reactive nature of this instability. Further investigation reveals the similarity of our reactive EGAMs to the well-known two-stream instability. We have applied our results to the early turn-on of EGAMs in DIII-D by considering a single energy single pitch beam distribution function, before the slowing-down or pitch angle scattering occurs. For the DIII-D beam in Nazikian *et al*[7], we model a mono-energetic beam with energy E_0= 75 keV and pitch angle Λ_0= 0.5, and compute the average fast ion transit frequency $\omega_b = 0.88\omega_{GAM}$ obtained from $T_e = 1.2T_i \approx 1.2$ keV and q = 4 at the radial localized flux surface s = 0.4. Figure 2c show the real frequency and growth rate of the reactive EGAM as a function of α, the fast ion density fraction. The frequency of the reactive EGAM stays reasonably close to the observed frequency (28 kHz) for α > 3%.

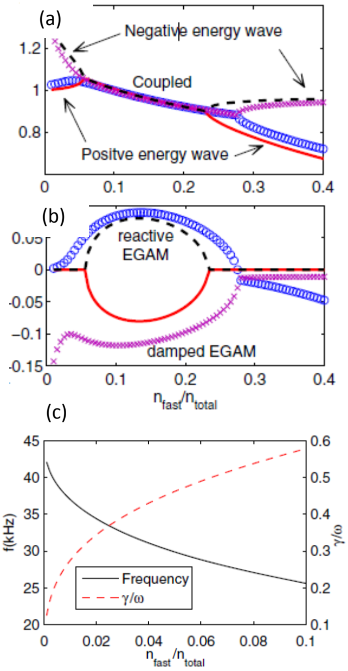

Fig. 2: Real frequency (a) and growth rate (b) versus fast ion density for multifluid model with comparison to kinetic theory, for q = 2 and $\omega_b = 1.76\omega_{GAM}$. Lines (symbols) represent fluid (kinetic) results. (c) Real frequency and growth rate of the reactive EGAM using DIII-D parameters on flux surface s = 0.4.

As is well known, in an ideal MHD plasma, shear Alfven eigenmodes may experience dissipation-less damping due to resonant interaction with the shear Alfven continuum. This continuum damping can make a significant contribution to the overall growth/decay rate of shear Alfven eigenmodes, with consequent implications for fast ion transport. One method for calculating continuum damping is to solve the MHD eigenvalue problem over a suitable contour in the complex plane, thereby satisfying the causality condition. The complex contour method, developed by Koenies and Kleiber[8] has been applied to the three-dimensional finite element ideal MHD Code for Kinetic Alfven waves[9]. We review the application of the complex contour technique to calculate the continuum damping of global modes in tokamak as well as torsatron, W7-X and H-1NF stellarator cases. These stellarator calculations represent the first calculation of continuum damping for eigenmodes in fully three-dimensional equilibria. [4]

Finally, we also report on progress in the modelling of fully 3D fields with Multiple Relaxed region MHD, or MRxMHD, a generalisation of Taylor's theory, in which the plasma is partitioned into a finite number of nested regions that independently undergo Taylor relaxation. The plasma regions are separated by ideal transport barriers that are also assumed to be magnetic flux surfaces. We examine the relationship between flux surface irrationality, MRxMHD stability, tearing mode stability, as well as report on extensions of MRxMHD to include field-aligned and toroidal flow, and pressure anisotropy.

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