ENERGETIC PARTICLE DISTRIBUTIONS FOR QUANTITATIVE CALCULATIONS OF BURNING PLASMA STABILITY

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Energetic particles can drive a variety of instabilities in tokamak plasmas which can affect fusion performance. Consequences of these instabilities include a performance-degrading outward transport of high-energy fusion-born alpha particles before they thermalize with the bulk plasma [1] and the beneficial moderation of turbulent transport [2]. In all cases it is gradients in the distribution of energetic particles, in both real and velocity space, that determines the strength of the power transfer from these particles to modes in the plasma. To be able to make quantitative predictions, it is thus necessary to accurately represent the distributions.

A quantitative assessment of the stability of plasmas containing energetic particles requires a proper description of the distribution of energetic particles in 6-dimensional real and velocity space. In axisymmetric fusion-relevant tokamak plasmas, in addition to the conservation of energy, E, and magnetic moment, μ, toroidal canonical angular momentum, P_φ, is also conserved and allows steady-state distribution functions to be written in terms of just these three invariants or constants-of-the-motion, $f(E, \mu, P_\varphi)$. In this work we describe the development of a software tool to transform between different numerical representations of energetic particle distributions and a constants-of-the-motion form.

Energetic particles arise in fusion plasmas as a consequence of the use of external auxiliary heating systems such as neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH). Both of these heating systems produce populations of fast ions that are characterized by the underlying mechanisms by which they work. NBI injects neutral atoms with a characteristic energy into the plasma which are ionized and then slow-down first through collisions with electrons, and then with other ions, leading to a characteristic slowing-down distribution in energy. ICRH accelerates ions through a resonant exchange of energy in the cyclotron frequency range and leads to highly anisotropic distributions of trapped fast ions. D-T fusion reactions in the core of burning plasmas produce a nearly isotropic distribution of alpha particles that also form a slowing down distribution from their characteristic birth energy of 3.52 MeV.

In all of the above cases, the distribution of fast ions found by solving the appropriate Fokker-Planck equation significantly deviates from a Maxwellian distribution. This, coupled with the fact that it is the gradients in the energetic particle distribution function that provides the drive for energetic particle driven instabilities, motivates the need for a quantitative representation of energetic particle distributions in fusion plasmas that can be transformed between different representations for use within different stability and transport codes. In this work, a method is developed within the ITER Integrated Modelling & Analysis Suite [3] (IMAS) to transform numerical representations of energetic particle distribution functions into arbitrary coordinates via a representation in constant-of-motions (CoM) space which is ideal for first principles and stability codes as it intrinsically represents stationary equilibrium distributions. Such a transformation is performed for a given experimental configuration (magnetic equilibrium) by computing the energetic particle trajectories on a grid of CoM coordinates. Properties of these trajectories enable the calculation of the CoM Jacobian which depends on the poloidal bounce / transit times and enables distributions to be transformed to CoM space. The distribution in CoM space is then represented by 3D $\mathcal{C}^2$ B-splines, to ensure a strictly continuous representation for stability and nonlinear simulations. The intrinsic singularity that arises at the trapped-passing boundary [3] is eliminated by splitting the distribution into co-going and counter-going components, $\sigma = v_\parallel/|v| = \pm 1$, for both trapped and passing particles, which enables enforcement of the $\mathcal{C}^2$ condition. The consistency of the transformation between representations is successfully demonstrated by performing multiple transformations between spaces for distributions obtained from Fokker-Planck calculations for DIII-D, JET and ITER plasmas. Different techniques are then presented to initialize energetic particle distributions in codes using either δf or full-f methods. These schemes are demonstrated using the δf gyrokinetic code GTC [4] and the full-f kinetic-MHD code XTOR-K [5].

Furthermore, the calculation of orbit properties including the poloidal and toroidal transit frequencies, ω_θ and ω_ϕ, allows the identification of the surfaces in phase-space where a resonant exchange of energy between the energetic particles and a plasma mode with a give frequency, ω, and toroidal mode number, n, can occur. Namely where $\omega - n\omega_\phi + p\omega_\theta = 0$ with p an integer [6]. This information, when combined with the gradient that drives instabilities, $n\frac{\partial f}{\partial P_\phi} + \omega\frac{\partial f}{\partial E}$, allows the regions of phase space responsible for observed instabilities to be identified.

The following example in which the fast ion distribution in a DIII-D plasma is changed by switching between NBI sources helps validate the approach. Fig. 1 shows the regions of CoM phase space where an n = 5 core-localised BAE mode interacts with neutral beam ions in a DIII-D plasma [7]. The red area indicates the region of CoM space where fast ions fully overlap with the BAE, and the green area where they only partly overlap. Figs. 2 and 3 shows the resonance lines for the observed mode as black lines overlaid upon a coloured contour plot showing the drive the fast ion distribution provides to the mode. In Fig. 2 tangential NBI is used while in Fig.3, perpendicular NBI heating, which leads to the disappearance of the BAE in the experiment [7]. A slight change in the q-profile between the time points means the resonance lines move slightly whilst the change in injection geometry means the distribution in Fig. 3 contains more trapped ions. The red and blue lines in Figs. 2 and 3 indicate the boundaries of the regions in Fig 1. It can be seen that the fast ions that lie along the p = 6 resonance line (a necessary but not sufficient condition for energy exchange) and that wholly overlap with the mode (inside the red boundary) are in a region of stronger drive in Fig. 2 compared to Fig. 3. This is consistent with the experimental observation of the mode existence in Fig. 2 but its disappearance in Fig. 3.

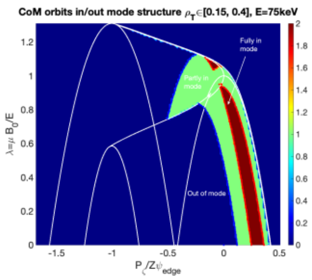

Figure 1: Red region shows particle orbits that wholly overlap with BAE region. Green region shows particle orbits that partly overlap with BAE region.

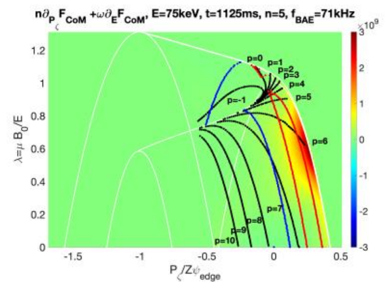

Figure 2: Black lines show resonances for n = 5 BAE overlaid on colour map showing strength of distribution gradient (drive for mode). Red line outlines region where orbits wholly overlap with mode localization.

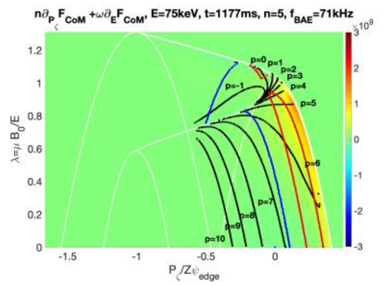

Figure 3: Black lines show resonances for n = 5 BAE overlaid on colour map showing strength of distribution gradient (drive for mode). Red line outlines region where orbits wholly overlap with mode localization.

Further gryrokinetic and kinetic-MHD simulations of these DIII-D observations will be presented and are being undertaken as part of an on-going ITPA activity. BAE stability properties and the related nonlinear energetic particle transport will be compared between cases, including realistic CoM distributions and their Maxwellian equivalents, to highlight the impact of realistic distributions on the dynamics of fast ion driven modes.

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