Contribution ID: **675** Type: **Regular Poster**

Nonlinear dynamics and stability surveys of energetic particle instabilities

Tuesday 11 May 2021 12:10 (20 minutes)

Energetic particle (EP) instability models based on gyro-Landau closure techniques (1) have addressed important nonlinear simulation and linear stability survey challenges that will be critical for the understanding and control of burning plasmas in ITER and the next generation of fusion systems. The long-term intermittency and frequency spreading characteristics of saturated Alfvén instabilities (Fig. 1) are important features that will determine peak wall heat loads from escaping energetic ions as well as play a central role in regulating energetic particle anomalous transport levels. Reduced models using gyrofluid closures such as the TAEFL (2) and FAR3d (3) models, allow routine simulation of Alfvénic instabilities far into the nonlinear regime and demonstrate the dependence of the nonlinear dynamics on source-sink balances, zonal flow/current damping, and turbulence levels in the thermal plasma (modeled in Fig. 1 using diffusivities). The efficiency of this approach also facilitates linear instability surveys as profiles/parameters/plasma shapes are varied (Fig. 2); this capability is essential for simulating the dynamical changes that occur in realistic simulations of tokamak discharge evolution.

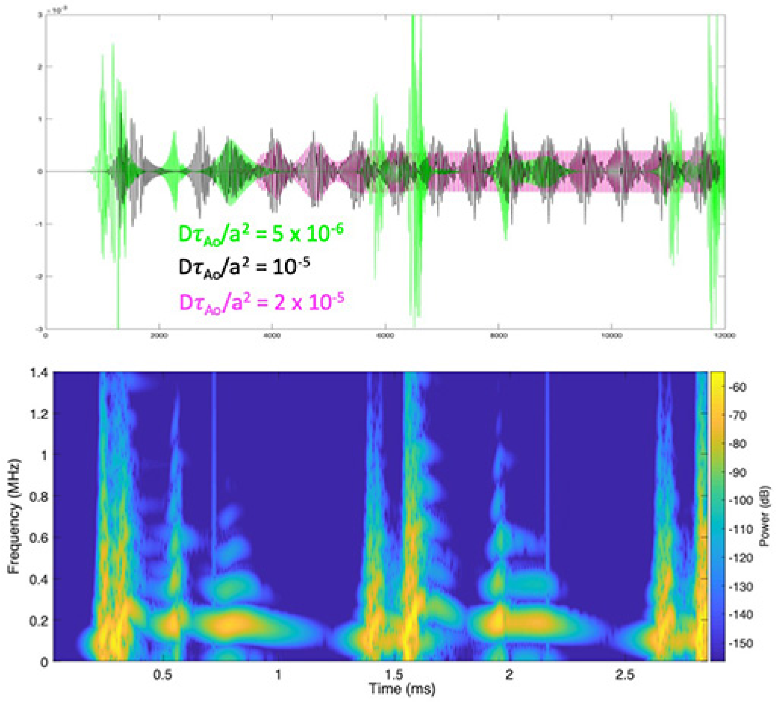

Figure 1: Simulated evolution of $\delta B_\theta/B$ and frequency spectrogram of AE instability for DIII-D discharge #176523 with varying diffusivities (spectrogram in bottom figure is based on green waveform in the top figure).

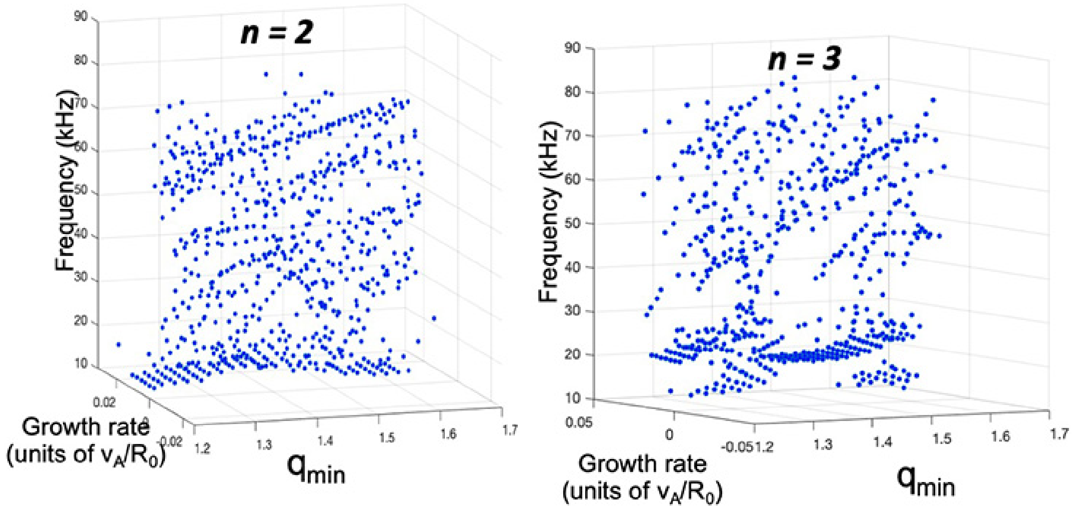

Figure 2: Low frequency Alfvén-acoustic instability surveys for a sequence of 21 q-profiles based on DIII-D discharge #144094.

Reduced physics models for EP instabilities based on gyro-Landau closures (2,3) offer a computationally efficient tool for understanding effects of macroscopic parameters that control the saturated turbulent state of these instabilities. These models are based on an optimized set of closure coefficients that provide good fits to response functions derived from kinetic theory. Wave-particle resonances that exist in phase space are effectively mapped into real space while preserving growth/damping effects associated with EP energy distribution functions. These reduced models have been checked against more complete models (4). In the nonlinear regime, mode-coupling nonlinearities that drive zonal flows, zonal currents, localized flattening in the EP pressure profile, and couple to damped modes are included. The viability of simulating EP modes far into the nonlinear limit with these models is based on using a third order predictor-corrector time stepping algorithm, and the fact that there is no particle noise or small perturbation ordering, as typically limits simulation times for particle-based models. In regimes with moderate drive, balanced sources/sinks and where zonal flows/currents dominate, predator prey phenomena (5) are evident (black waveform in Fig. 1). As diffusivities are lowered or instability drive is increased, bursting phenomena and frequency chirping are observed (green waveform in Fig. 1). Saturation into a steady level can be achieved as EP drive is diminished by EP profile changes (Fig. 3). EP nonlinear transport fluxes (Fig. 4) and 3D convection cell phenomena can also be predicted.

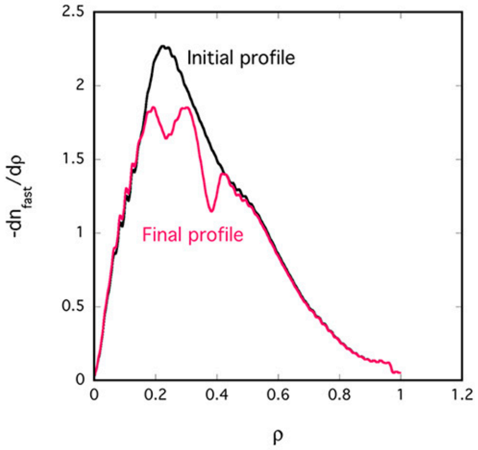

Figure 3: Erosion of EP density gradient by nonlinear AE instability

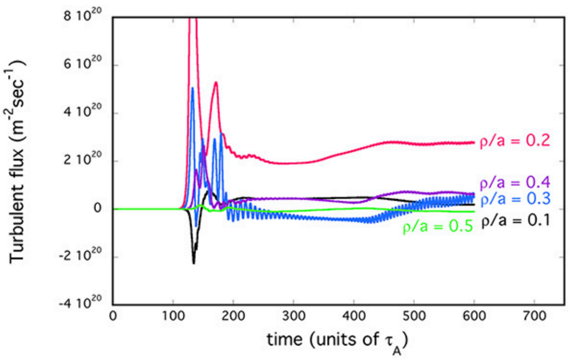

Figure 4: EP instability-driven density fluxes vs. time and radial position.

The reversed shear/high bootstrap current tokamak regime offers the possibility of steady-state operation but is often unfavorable for EP-driven instabilities. Reversed shear/high bootstrap current discharge formation is a dynamical process and EP instability evaluation requires consideration of evolving profiles/parameters and plasma shapes. The gyrofluid model provides a unique, efficient multiple eigenmode solver approach that has been applied to these regimes. Low frequency Alfvén-acoustic (BAE/BAAE) instabilities are of particular concern since they can lead to larger radial transport levels than higher frequency AE modes (6). The survey capability of FAR3d has been applied to a DIII-D discharge with evolving q-profiles where multiple low frequency modes were observed (Fig. 2) and the results have shown similarities with the mode frequency evolution from the experiment.

This work was supported by the U.S. Department of Energy under DE-AC05-00OR22725, DE-FC02-04ER54698, and the U.S. DOE SciDAC ISEP Center.

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Session Classification: P1 Posters 1

Track Classification: Magnetic Fusion Theory and Modelling