Analysis of Hybrid Kinetic-MHD Simulations

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We present novel phase space diagnostics of δf kinetic-MHD[1] linear simulation study of energetic particle effects on the $n = 1$ mode in a "hybrid" DIII-D discharge. These discharges are limited to moderate $\beta_N \sim 2.5$ by the $m/n = 2/1$ instability. A past study has shown[2] that energetic particles significantly change the stability map in (q_{min},β_N) parameter space from the MHD-only result and may help in explaining the experimental results. Unstable modes are driven by energetic particles far into the MHD stable region in (q_{min},β_N) space. Three different unstable regions are identified. At low $q_{min} \sim 1$ the drive is associated with the fishbone mode, while the higher $q_{min} \gtrsim 1.12$ the drive is associated with the BAE mode. We apply these new phase space diagnostics to examples from these three regions. These new diagnostics complement conventional diagnostics that are commonly used and will help in identification and analysis of the mode/particle interactions.

I. INTRODUCTION

In previous analysis[2], we computed the linear stability of the $n = 1$ mode of a DIII-D "hybrid" discharge[3] with a low central shear and $q_{min} \gtrsim 1$. Using an experimental equilibrium reconstruction, we generated a series of neighboring equilibria varying q_{min} and β_N. For each of these equilibria, we ran linear NIMROD simulations with and without energetic particles and computed the growth rates and real frequencies of the $n = 1$ mode, with Lundquist number $S = \tau_R/\tau_A \sim 10^7 - 10^8$, fixed Prandtl number $Pr = \mu_0\nu/\eta = 100$, and fixed $\beta_{frac} = \beta_h/\beta = 0.16$ representative of DIII-D conditions. A stability map in (q_{min}, β_N) space was constructed and revealed a significant change due to energetic particle effects. The energetic particle stability map naturally divides into three distinct regions characterized by the real frequency of the $n = 1$ mode. We present applications of novel phase space diagnostics to analyze example eigenmodes from these three region.

These diagnostics examine the evolution of δf in $(v_\parallel, v_\perp)$ space and convolution of the terms in the δf[4] evolution equation. We also examine the contributions from passing and trapped subpopulations and show that both subpopulations contribute significantly to energetic particle-MHD mode evolution. In particular, this phase space analysis reveals that the region near the trapped/passing boundary is a key region of activity.

The intent of these new δf PIC phase space diagnostics is to help elucidate the physics of energetic particle interactions with MHD modes. The analysis is in its developmental stage and primarily phenomenological, but continued development and refinement will mature these tools to quantitative and potentially predictive measurements.

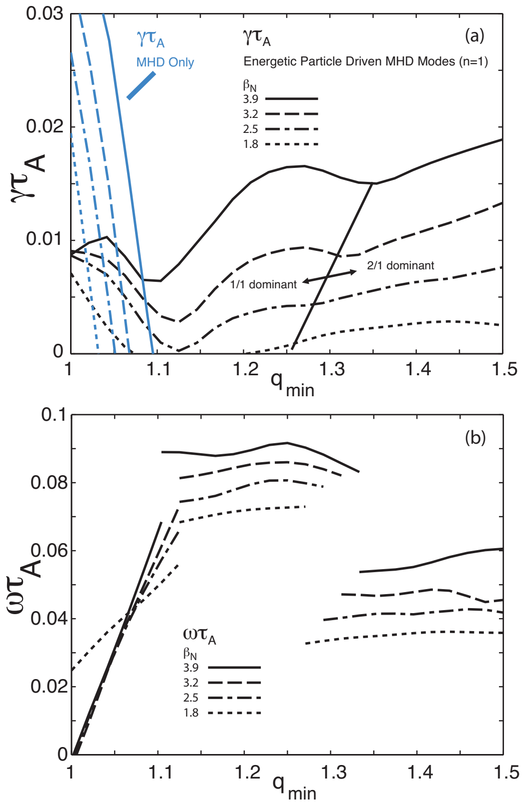

FIG. 1: Growth rates and real frequencies of the $n = 1$ mode vs. q_{min} for set of β_N values. Also shown are MHD-only results.

II. ENERGETIC PARTICLE EFFECTS

Fig. 1 summarizes several scans in q_{min} at different fixed pressures and plot growth rate and frequency vs. q_{min} for a series of fixed β_N values. For comparison, the MHD-only growth rates are also plotted. The real frequency response shows a natural division into three distinct regions. The MHD-only simulations show stability above $q_{min} \simeq 1.07$. The energetic particle inclusive growth rates show that in the lower q_{min} region, energetic particles reduce the growth rate. This region also shows a linear dependence of the real frequency on q_{min}. Above $q_{min} \simeq 1.12$, the real frequency shows a weak dependence and then makes an abrupt transition to lower, near constant frequency.

The energetic particle interaction with the mode can be divided into three regions in (q_{min},β_N) space, characterized by the frequency response $(\omega\tau_A)$. We examine example eigenmodes from these three regions in Figs 2,3.

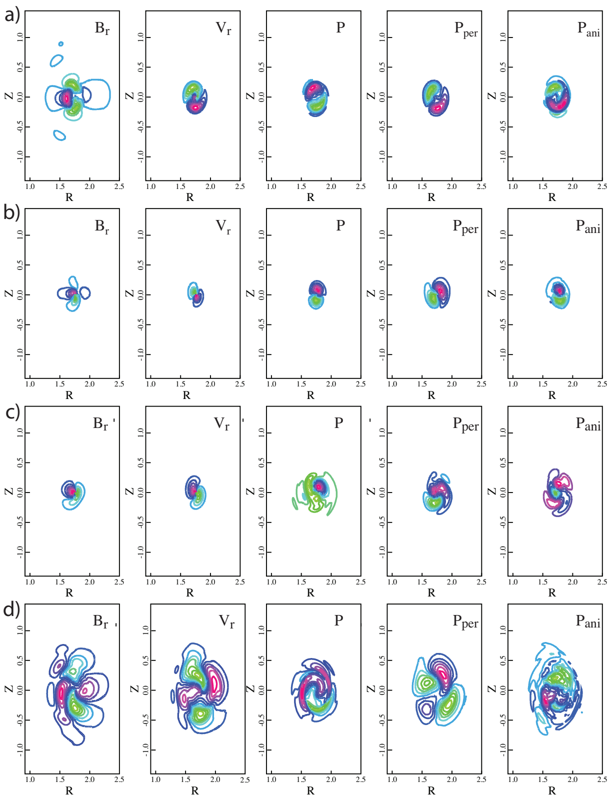

FIG. 2: The flux normal magnetic field and velocity, fluid pressure, particle perpendicular pressure and particle anisotropic pressure eigenfunctions for q_{min} of a) 0.95, b) 1.05, c) 1.21 and d) 1.36.

For the first region, [Fig 2(b)($q_{min} = 1.05$,$\beta_N = 3.0$)]the perturbed pressure retains a non-resonant $m = 1$ structure peaked near the magnetic axis, while the B_r perturbation is dominantly $m = 2$. The next two regions are in the stable regions of the MHD-only stability map. These low growth rate (compared to ideal MHD), high frequency (compared to growth rate) modes are predominantly energetic particle driven Alfven modes. For the ($q_{min} = 1.21$,$\beta_N = 2.6$) case [Fig 2(c)], the 1/1 structure near the axis persists. At the higher q_{min} case [($q_{min} = 1.36$,$\beta_N = 2.3$)Fig 2(d)], the eigenmode extends out to the $q = 2$ rational surface with $m = 2$ structure, and no $m = 1$ non-resonant structure appears near the axis.

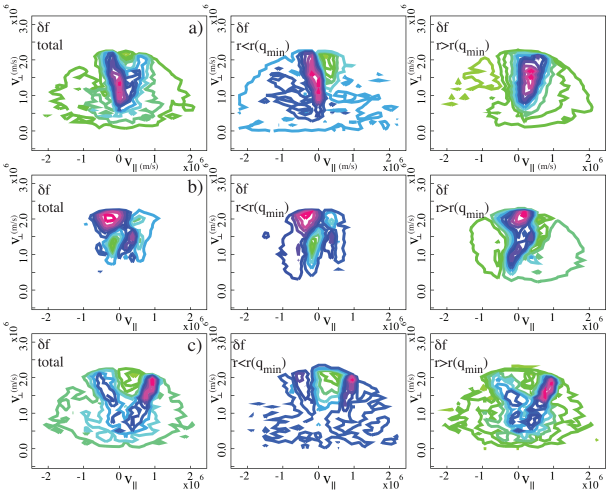

FIG. 3: The real part of the $n = 1$ "velocity-space" eigenmode for three cases with q_{min} of a) 1.05, b) 1.21 and c) 1.36.

We consider an orthogonal view of the n=1 mode in "velocity-space" of the particles, i.e.

$$\delta f(v_\parallel, v_\perp)_{n=1} = \int_{r_1}^{r_2} \delta f(\mathbf{z}) d^3x|_{n=1}. \qquad (1)$$

These are shown in Fig. 3 for the same cases as Fig. 2 above. We also compare the $n = 1$ "velocity-space" eigenmode integrated over subvolumes, from the axis to the q_{min} minor radius($r_1 = 0, r_2 = r(q_{min})$) and from the q_{min} minor radius to the outer boundary($r_1 = r(q_{min}), r_2 = a$). Each "velocity-space" eigenmodes is distinct.

We will detail this orthogonal view and its relation to the configuration space eigenmode and present accompanying diagnostics of the phase space evolution of these energetic particle, kinetic-MHD simulations.

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