Energetic particle effects on n=1 and n=2 tearing modes in a DIII-D discharge

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Tokamak experiments where $q_{min} \sim 1$ commonly show an $m/n = 3/2$ neoclassical tearing mode (NTM) (where m is the poloidal wave number, n is the toroidal wave number) evolving during the slow β ramp up and "flattop" steady state, before the onset of an $m/n = 2/1$ NTM. Energetic particles from neutral beam injection affect both modes differently, making the underlying physics puzzling. In theoretical and numerical calculations of the MHD stability of these configurations during the flattop stage, the ideal limit in β_N (where $\beta_N = \beta/(I/aB_T)$, $\beta = 2\mu_0 P/B^2$, P is pressure, and B_T is toroidal magnetic field) of the $n = 2$ is higher than the $n = 1$. The $3/2$ mode typically onsets early in the discharge when the rational surface comes into existence off axis in a reversed and weak q shear. Later in the discharge the $2/1$ can onset with or without the $3/2$ mode present in its nonlinear saturated state.

The focus in this paper is the energetic particle effects on the linear $n = 1$ and $n = 2$ modes in this type of discharge. We computationally analyze these effects using a δf PIC model for the energetic particles coupled to the nonlinear 3-D resistive MHD code NIMROD[1, 2], as well as the resistive stability code PEST-III[3] and the ideal stability code DCON[4].

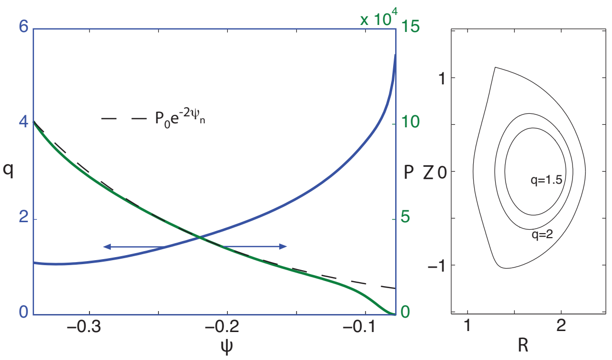

Figure 1: The shape, pressure, and q profiles of the equilibria used in this study.

A single discharge is analyzed in this paper, which is taken from an experiment on DIII-D to study the evolution of the $3/2$ and onset of the $2/1$ modes[5]. In Ref.[5] the effect of flow shear on the $3/2$ and $2/1$ modes is characterized by a change in the effective linear drive to the island evolution. Our overall motivation is aimed at including energetic particle physics into such a study, which also affects the modes. Initially, we map the linear growth rates of the $n = 1$ and 2 modes for a series of equilibria that are based on an experimental equilibrium reconstruction during the flattop, before onset of the $2/1$ mode, with varying q_{min} and β_N. This gives context to the physics describing the instabilities, and is relevant to any such discharge. We then take a fraction of β to be from energetic particles as in Ref.[6], to study their effect.

The equilibrium profiles in the reconstruction are shown in Fig.1. Here $q_{min} = 1.06$ and $\beta_N = 2.5$. Note that in the hybrid discharge configuration, the q_{min} hovers just above 1. This non-resonant but significant $1/1$ and $2/2$ response around the magnetic axis plays a critical role in the physics of the equilibrium state, and is sensitive to small changes in q_{min}. In particular it has been shown to affect the ideal and resistive stability[7].

The trajectory of the experimental discharge in q_{min}, β_N space can be seen in Fig. 2. This trajectory is taken from an automated set of equilibrium reconstructions from the experiment, and thus does not exactly intersect the accurate kinetic equilibrium reconstruction used as a basis for the stability analyses. Initially, the experiment begins at low β_N and high q_{min}, and subsequently is ramped up to the relatively steady state where the stability analysis is performed. The analysis is then valid for the entire flattop, but is not pertinent to the early time (where the $n = 2$ mode onsets) nor the later time (after the flattop).

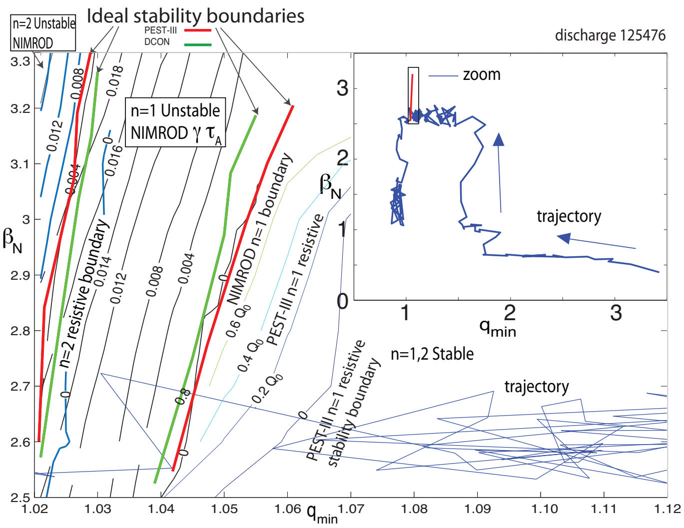

Figure 2: Contours of $\gamma\tau_A$ from NIMROD, the ideal stability boundaries calculated by PEST-III (red) and DCON (green) for the n=1 and n=2 modes, and the trajectory of the experimental discharge.

The NIMROD (MHD only), PEST-III and DCON results for the $n = 1$ and 2 modes are shown in Fig. 2. The resistive MHD threshold in PEST-III is computed with an inner layer model as in Refs. [7], including both the tearing and interchange parities, where an eigensolution for the growth rate Q is found. Experimental values for temperature and density are used for the inner layer resistivity. The configuration used in NIMROD has $S \equiv \tau_R/\tau_A \approx 2.7 \times 10^7$ and a viscous Prandtl number $Pr \equiv \mu_0 \nu/\eta = 100$.

The comparison between NIMROD, PEST-III and DCON results indicates that the boundaries for onset of the $n = 1$ and $n = 2$ modes are in broad agreement. The NIMROD calculations show a slightly lower resistive threshold in q_min, liekly due to differences in the models. The experimental profiles hover outside of the unstable zone for the $n = 1$ mode. The $3/2$ island is present throughout the flattop stage, in a nonlinear saturated state. Note that the inclusion of energetic particles strongly affects these boundaries as shown below.

Energetic Particle Effects

It is important in the specification of the pressure in the weight equation for the energetic particles to match the equilibrium configuration of fluid pressure. We therefore approximate the pressure with the dependence $P \sim P_0 \exp -2\psi$ as shown in Fig. 1 which is close to the equilibrium pressure throughout most of the radius, up to the edge pedestal region.

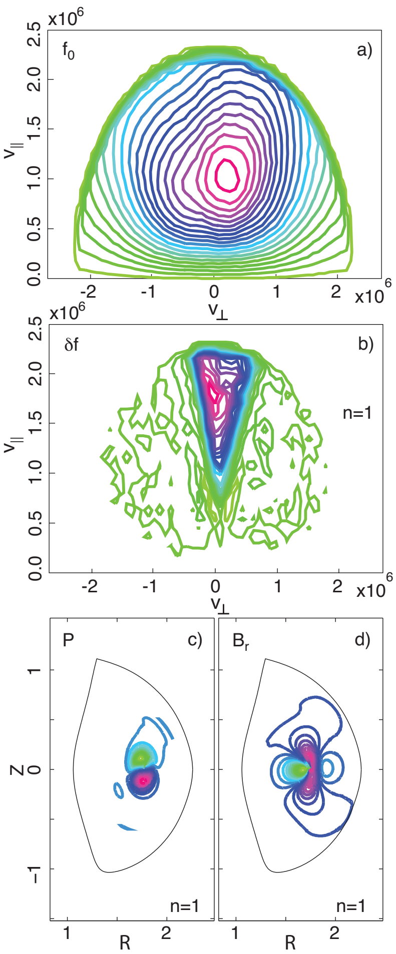

Figure 3: The f_0, δf, perturbed $n = 1$ pressure and surface-normal magnetic field.

The maximum energy of the particles $\varepsilon_{max} = 50keV$ and the critical energy $\varepsilon_c = 10keV$ in the "slowing down" distribution, emulating neutral beam deposition. The fraction $\beta_{frac} = \beta_h/\beta$ of thermal energy in the particles is held fixed at 16%.

Our recent studies of energetic particle effects on $2/1$ modes[6] focused on equilibria with $q_{min} \sim 1.5$ and $\beta_N \sim 2-3$, with cross-section emulating so-called "advanced" configurations in tokamak experiments. In the current study we compare the energetic particle effects on the $n = 2$ and $n = 1$ modes in the so-called "hybrid" configuration with $q_{min} >\sim 1$.

The $n = 1$ and $n = 2$ eigenfunctions are shown in Fig.3. These eigenfunctions indicate an important difference between the hybrid and high q_{min} results. The non-resonant $1/1$ component is visible in the core pressure perturbation. However, the B_r perturbation remains dominantly associated with the $2/1$. In the high q_{min}, both are $2/1$ dominant. Asymmetry is evident in f_0, and the prominence of the trapped cone in δf indicates that it is primarily the trapped and barely passing particles that are interacting with the mode.

As seen in Fig. 4, at lower q_{min} than experimental, near $q_{min} \sim 1$, the growth rates for the ideal unstable mode are weakly affected by the energetic particles. However, at slightly higher q_{min}, the non-resonant component of the mode interacts with the particles and both increases the growth rates of resistive unstable modes and destabilizes the mode in MHD stable regions. The stability boundaries for both modes are effectively pushed to higher q_{min}.

Previously, we have shown that for $m/n = 2/1$ modes with $q_{min} \sim 1.5$, energetic particles have significant damping and stabilizing effects at experimentally relevant β_N and $\beta_{frac} = \beta_h/\beta$

(β_h is the energetic particle β) and weaker damping and stabilizing effects in the ideal unstable regime, and excite a real frequency of the 2/1 mode[6]. In the hybrid configuration the real frequencies are excited, and the response in the ideal unstable regime is similar. However, the interaction of the particles with the non-resonant response on axis causes destabilization of the mode as opposed to a damping effect in the higher q_{min} cases.

The most significant effect is that on the n=1 mode. The n=2 mode is driven, but in a smaller band of q_{min} nearer the MHD boundary. The $n = 1$ mode is driven unstable up to $q_{min} \sim 1.2$. Though modest changes are observed with the increase in $\beta_N = 2.5 \rightarrow 2.9$, significantly higher β_N should approach the ideal limit for all q_{min}. It is an open question whether there is evidence for such an energetic particle effect on the 2/1 onset in the experimental data. The effect the particles have on the stable $n = 2$ mode, and the nonlinearly saturated 3/2 islands, is not directly addressed by this study, but would be needed to address the nonlinear evolution. This is a focus of our current efforts, as is the development of energetic particle effects into the PEST-III code.

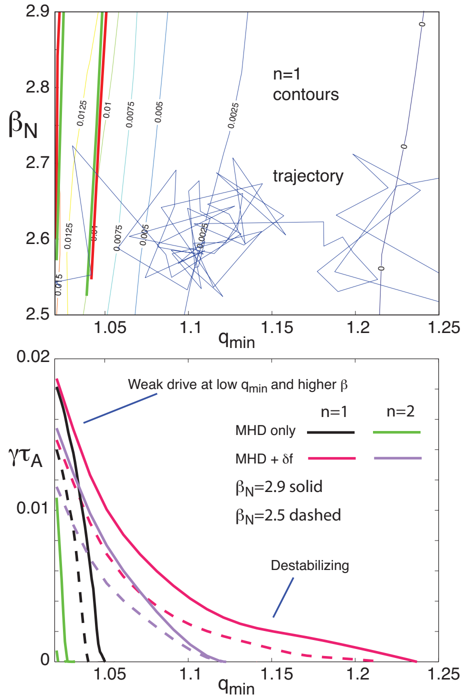

Figure 4: The growth rates with energetic particle effects.

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