Self-consistent simulation of tearing modes during ECCD experiments on TCV

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Introduction

Neoclassical tearing modes have been studied extensively as they are the main reason for confinement degradation and limited beta in large Tokamaks. Substantial modeling efforts, backed up by experimental comparisons have confirmed the necessity of a seed island exceeding a critical island size to overcome stabilizing effects of curvature and pressure at small island size. Tearing modes observed in the TCV tokamak, with electron cyclotron current drive (ECCD), have been shown to be classically triggered [4], meaning they do not require an initial seed island to appear but are destabilized by the properties of the current profile. Recently, modes have been seen to appear in so-called Swing-ECCD (SECCD) discharges [1]. During these discharges two sets of gyrotrons were aimed to provide alternating co and counter-ECCD at the same deposition location. A tearing mode is repeatedly triggered during the co-ECCD phase as can be appreciated from the spectrogram in Figure 1(a).

Since the total input power is kept approximately constant, the tearing mode is triggered by a change in the local current density profile, acting to change the classical tearing parameter $r_s\Delta'$. This has motivated the present study to attempt to simulate the appearance of the TCV tearing modes, as a benchmark for existing codes and models.

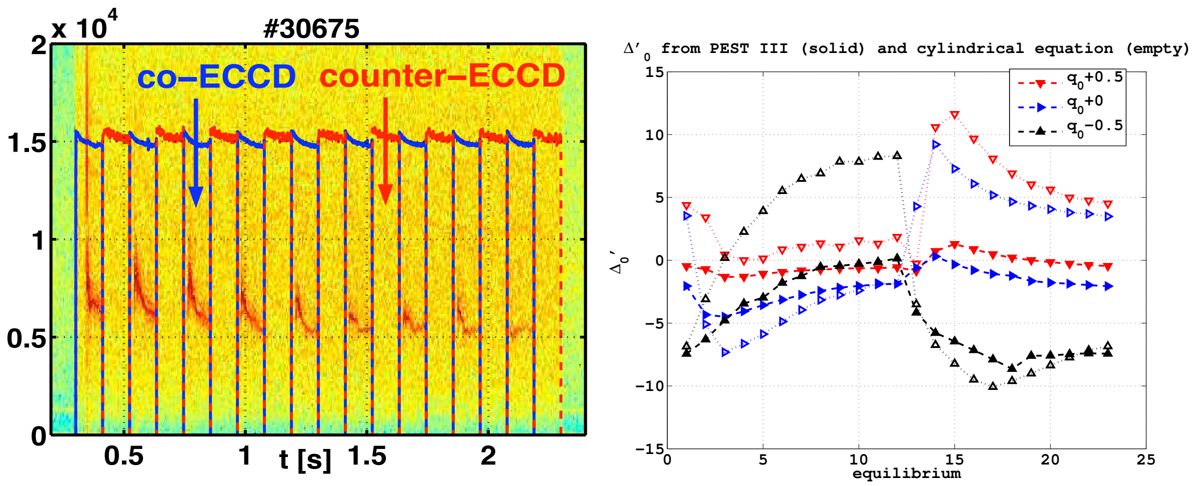

Figure 1: Left: (a) MHD spectrogram of TCV swing-ECCD shot 30675. Right: (b) Δ'_0 calculations based on simulated equilibria of co (#1-12) and counter (#13-23) ECCD phases.

Self consistent tearing mode simulation

Tearing modes are modeled using the Modified Rutherford Equation (MRE). This equation describes the growth rate of the tearing mode driven by various stabilizing and destabilizing parameters. Assuming that no heat or current is directly deposited inside the island, the simplest form of the MRE reads.

$$\frac{\tau_R}{r_s}\frac{dw}{dt} = r_s\Delta_0' + r_s\beta_p\left(\frac{w a_{bs}}{\sqrt{w^2+w_d^2}} - \frac{a_{GGJ}}{\sqrt{w^2+0.2w_d^2}}\right) \tag{1}$$

The various terms are described in detail in [5], [6]. In order to self-consistently simulate the evolution of tearing modes, not only the change in w has to be taken into account. The evolution of all the terms appearing in the MRE should be simulated self-consistently including changes in the coefficients a_{bs}, a_{ggj} and w_d, and also the Δ_0' term for which a simplified analytical form is usually employed. A possible scheme to accomplish this is outlined below. From given plasma shape, density, temperature, pressure and current profiles, the CHEASE equilibrium solver can compute not only the equilibrium but also most of the relevant terms needed to evaluate the coefficients of the MRE. The output from CHEASE can also directly be used as input to the PEST III [3] stability code, which calculates Δ_0' in toroidal geometry. Now that all the terms are known, the MRE can be integrated yielding the instantaneous growth rate and the resulting island width. The final step is to simulate the effect of the island on the pressure profile, modeled in a transport code as a local increase of conductivity and to evolve the kinetic profiles. The resulting profiles are then fed back into CHEASE for a new simulation step. One of the main bottlenecks in implementing such a scheme is the computational time taken by PEST III which is typically several seconds. One solution is to solve for the cylindrical Δ' which is obtained from the solution of

$$\frac{1}{r}\frac{d}{dr}r\frac{d}{dr}\psi - \left[\frac{m^2}{r^2} + \frac{m}{m-nq}\frac{q'}{rq}\left(3+\frac{rq''}{q'}-\frac{2rq'}{q}\right)\right]\psi = 0 \tag{2}$$

The SECCD shot shown in Figure 1(a) has been simulated using ASTRA [2] in interpretative mode. The resulting profiles have then been used to calculate the MRE terms. In particular, the ASTRA results were fed to both PESTIII and a cylindrical code for computation of Δ'. The relative dependence of Δ' obtained with PEST III is found to be well reproduced by the cylindrical approximation as is shown in figure 1(b). The results, however, appear to be highly sensitive to the q profiles used, as is shown from the different trend obtained by shifting the q profile.

Δ' sensitivity due to local q profile changes

In order to understand more precisely how local changes in the q profile affect the tearing parameter Δ_0', a parameter study was performed by perturbing a parabolic q profile and calculating Δ_0' using Eq (2). This equation has an integrable singularity at the rational $q = m/n$ surface. The resulting solution ψ has a jump in the logarithmic derivative at the resonant q surface which provides the value of $\Delta' = \lim_{\varepsilon\downarrow 0}\frac{\psi'}{\psi}\Big|_{r_s-\varepsilon}^{r_s+\varepsilon}$. Note that Eq. (2) depends on both the shear of q: $s_q = \frac{rq'}{q}$

as well as what can be defined as the shear of q': $s_{q'} = \frac{rq''}{q'}$. Moreover, the term $m/(m-nq)$ term shows that the result is mostly affected by the profiles close to the $q = m/n$ rational surface. Figure 2 illustrates the effect of local changes to either the rational surface location, the shear of q or the shear of q' at the rational surface. The profile perturbations were constructed such as to ensure that the other quantities at the rational surface were not changed. As can be seen, both increasing shear and increasing shear of q' results, in this case, in an increase of Δ'_0. Increasing r_s decreases Δ'_0. Another set of profiles was constructed with a perturbation of the local shear and a constant factor added to the q profile. This results in the rational surface location being slightly shifted to the left or right of the location of the perturbation. As can be seen in figure 2(b), this results in a radically different dependence of Δ'_0 on the shear. This is a qualitatively similar effect as derived in [7] from j_{cd} perturbations. It shows, though, that simulations of tearing modes including the precise effects of Δ'_0 are inherently difficult, as slightly different assumptions in the transport model will lead to small changes in q which can greatly affect the classical tearing stability. This is why the profiles should evolve self-consistently.

Tearing modes triggered by local q profile changes in TCV

In recent TCV experiments a more detailed scan of deposition location was performed in order to destabilize the mode in a controlled way and experimentally study the sensitivity of its appearance to the deposition location. For this purpose a scan of ECCD injection angles was done on a set of plasmas similar to the SECCD discharges. All plasmas had the same shape, with main parameters $n_e = 10^{19}\mathrm{m}^{-3}$, $I_p = 120\mathrm{kA}$, $B_T = 1.45\mathrm{T}$, and two gyrotrons in co-ECCD with $P_{ECH} = 2 \times 450\mathrm{kW}$. Only the injection angles were varied between the plasmas. A mode is consistently triggered in a scenario with co-ECCD, with one gyrotron fixed at $\rho_{dep} = 0.35$ and the other sweeping between $\rho_{dep} = 0.5$ to 0.25. MHD spectrograms from three discharges are shown in Figure 3. In the first plasma, a tearing mode is triggered which is paired with

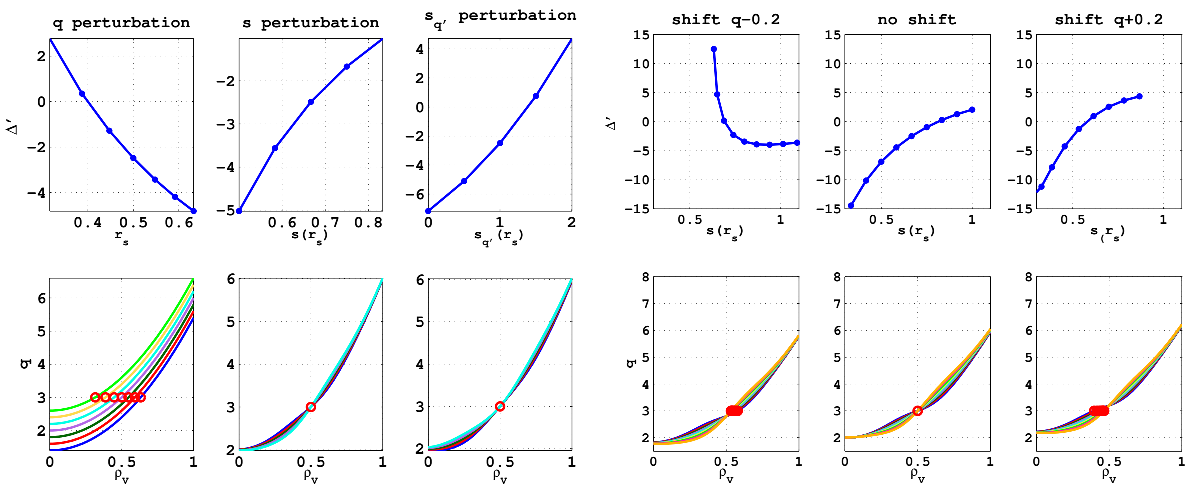

Figure 2: Left: (a) effects of local q, shear, and shear of q' profile perturbations on Δ'_0 Right: (b) A small global shift of q can greatly change the dependence of Δ' on the local shear

large sawtooth activity. When the deposition location moves inside the $q = 1$ surface the mode activity can be seen to become stronger. This is attributed to the enhanced neoclassical drive of the mode due to the better local confinement and higher β. The second plasma shows how the triggering of the mode occurs just by changing the launcher injection angle by 1 degree, corresponding to a change in deposition location of $\rho \sim 0.05$. The third plasma, finally, shows that simply depositing the ECCD current inside the critical deposition location does not, by itself, trigger the mode.

Conclusions and outlook

In order to model and understand the appearance of classically destabilized tearing modes in TCV, efforts were made towards self-consistent simulations integrating several aspects of tearing mode physics. Profiles coming from ASTRA simulations of Swing-ECCD discharges, which systematically featured the modes, were used to evaluate the various terms appearing in the modified Rutherford equation. The response of the classical tearing parameter to local changes in the q profile is shown to be very sensitive to details of the q profile and its derivatives, in particular the shear of q'. This makes detailed simulations difficult and warrants further experimental investigations. This also shows that all the profiles should be evolved self-consistently to represent the correct q profile evolution. Nevertheless we have shown that Δ_0' from cylindrical approximations follows well the results from PEST-III.

Detailed scans of the ECCD deposition location in recent TCV discharges confirms the sensitivity of the tearing mode appearance on the exact deposition location. Further TCV experiments should shed more light on the issue and can be used to confirm, the global trend of the Δ_0' dependence on locally deposited current.

References

[1] S. Cirant et al. In *21th IAEA Fusion Energy Conference*, 2006.
[2] G. V. Pereverzev and P. Yushmanov. Technical Report 5/98, IPP Report, 2002.
[3] A. Pletzer et al. *Journal of Computational Physics*, 115:530–549, 1994.
[4] H. Reimerdes et al. *Phys. Rev. Lett.*, **88**(10):105005, 2002.
[5] O. Sauter et al. *Plasma Physics and Controlled Fusion*, **44**(9):1999–2019, 2002.
[6] O. Sauter et al. *Physics of Plasmas*, **4**(5):1654–1664, 1997.
[7] E. Westerhof. *Nuclear Fusion*, **30**(6):1143–1147, 1990.

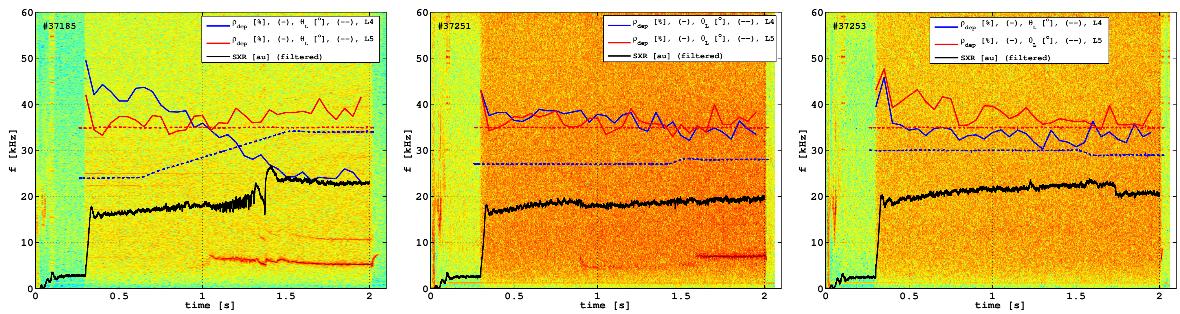

Figure 3: MHD spectrograms for three similar TCV shots, with and without modes