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Main Branches of the Error Field Amplification Resonance and their Properties

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Introduction. In advanced tokamak scenarios, the plasma performance is strongly limited by the external kink mode. This mode can be stabilized by plasma rotation but at the same time the error fields (arising for instance from asymmetric perturbations produced by the magnetic coils) can strongly amplify the mode and stop plasma rotation. Thus, the investigation of the error field amplification (EFA†) is one of the keys for an active control of Resistive Wall Modes (RWMs). The error field amplification can be well described in the linear MHD approximation. We have used the recently generalized linear MHD code CASTOR-FLOW[1] to investigate the interaction of the plasma with external error fields and to model experimental observations.

The ANTENNA version of the CASTOR-FLOW code. For the EFA investigations a new ANTENNA[2] part has been integrated into the CASTOR-FLOW code. In the code the problem is solved in two separate regions: the plasma region and the vacuum region. The solutions in both regions are connected at the plasma-vacuum surface. Wall resistivity is taken into account in the vacuum region via proper boundary conditions at the resistive wall. In the plasma region we solve the "driven problem"[3] (i.e. all perturbations inside the plasma are driven by the antenna and thus have the antenna frequency). Thus, it is possible to calculate the plasma response for a perturbation with given frequency. As a measure of this plasma response, the ratio of the magnetic field with plasma (B_{plasma}) determined on a control surface just outside the plasma, and the pure vacuum field without a plasma at the same control surface B_{vacuum} is used ($EFA = \left(B_{plasma} - B_{vacuum}\right) / B_{vacuum}$).

Results from the ANTENNA version of the CASTOR-FLOW code have been compared with a simple analytical model for error field amplification developed by R.Fitzpatrick[4]. We have reproduced the theoretical behaviour of the EFA resonance by

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† also known as RFA (Resonant Field Amplification)

changing the stability of the plasma against a kink perturbation (varying the position of the wall or the β_N -value)[2]. Our CASTOR-FLOW code is similar to the linear resistive MHD code MARS[5]. Preliminary benchmark calculations show very good agreement between these codes. Further benchmark calculations are in progress.

The „ideal branch“ of EFA resonance. Calculations with the CASTOR-FLOW code show that the error field amplification has two main branches of resonance: The first, so-called "ideal branch" of the error field resonance has a rather high frequency (about 0.2% of the Alfven frequency). A resistive wall behaves like an ideal wall at these frequencies, and the wall resistivity is not important. Thus, this branch appears even in the presence of an ideal wall. The strongest influence onto this branch is given by the coupling of the external kink mode to sound waves (compressibility Γ=1.667). This interaction reduces the resonant frequency and completely changes the resonance behavior[6] (figure 1). For a realistic compressibility, the frequency and the toroidal torque amplitude slightly increase with the wall distance. As seen from Fig. 1, Landau damping is

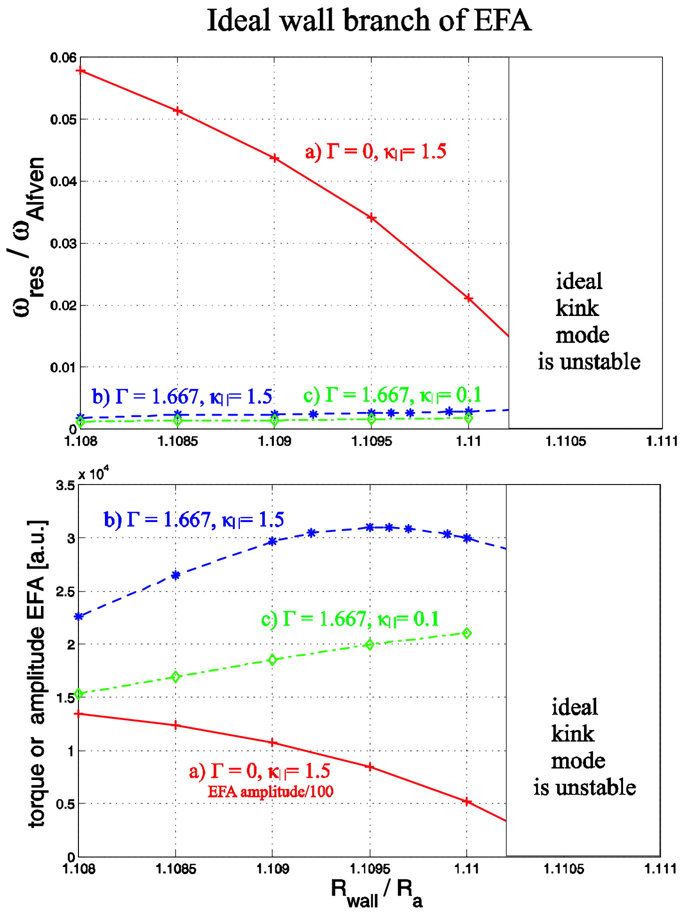

Figure 1. Influence of the sound wave coupling on the ideal branch of EFA: a) without coupling b) with coupling and strong Landau damping c) with coupling and weak Landau damping

important for the resonance amplitude as well. In the CASTOR-FLOW code Landau damping is modeled by a parallel force model[7], using a free parameter $\kappa_{\|}$. The other factors (perpendicular viscosity etc.) also change the resonance but to a much lesser degree.

The Resistive Wall Branch of EFA resonance. The second, so-called “resistive wall” branch requires a finite resistivity of the wall and has a much lower resonant frequency (comparable with the inverse resistive wall time). This branch mainly depends on centrifugal force and Landau damping. The centrifugal force becomes important for high values of plasma rotation (higher than 0.1 Mach), which is usually achieved in advanced tokamak scenarios in present day machines. The CASTOR-FLOW code includes the centrifugal force by dividing pressure perturbations into density and temperature perturbations. A set of calculations have been made with and without the centrifugal force (figure 2). One can see that this force leads to an additional peak of the error field amplification near the "no-wall" limit (plasma becomes more unstable).

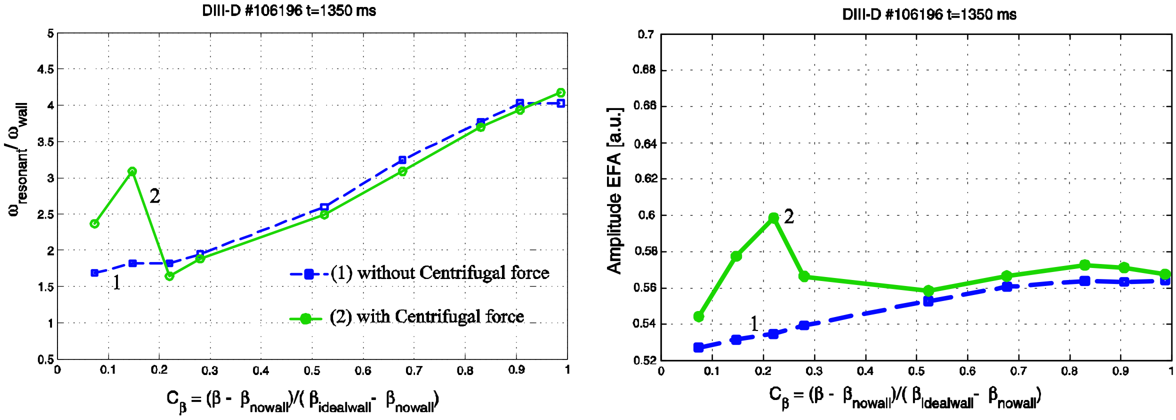

Figure 2. Influence of Centrifugal force on the resistive wall branch of the error field amplification resonance: 1) without Centrifugal force 2) with Centrifugal force

An experimental rotation profile from DIII-D was used for these calculations. In general, all calculations predict an increase of the resonant frequency towards the "ideal wall" limit. The error field amplification amplitude also slightly increases towards the "ideal wall" limit but reaches its maximum just before the "ideal wall" limit.

Comparison with DIII-D results. MHD spectroscopy experiments in DIII-D scan the plasma response for error fields at different antenna frequencies[8]. We can compare the results from these experiments directly with CASTOR-FLOW calculations. Fig.3 shows the resonance frequency and the EFA amplitude CASTOR-FLOW results, MHD spectroscopy results and MARS results together. (Experimental DIIID equilibria with $q_{98} = 6.2$ are used in all our calculations.) It was found that the poloidal antenna spectrum strongly influences the result. The results derived from our CASTOR-FLOW code (poloidal mode numbers *m=2...11*) are similar to MARS code calculations (here the equilibria for MARS and CASTOR are similar but not identical). Both codes predict a strong increase of the resonant frequency with increasing β-value and find resonant frequencies almost one order of magnitude higher than the measured values. The experimental antenna spectrum[9] however has significant contributions only for poloidal mode numbers *m=2…5*. Calculations with such a spectrum are much closer to the experimental observations. As in the experiments there is nearly no β-dependence of the resonance frequency and its values are similar to the experimental ones. For the EFA amplitude we compare only its β-dependence, which again is similar to the observations. The actual values of EFA amplitude measurements strongly depend on the specific geometry and positions of the probes as well as the coils in DIII-D which are not implemented in the code. The nearly absent β-dependence in these calculations can be explained keeping in mind that the main resonances excited by the antenna currents are located inside the plasma. Therefore the antenna does excite internal rather than external modes. The broader antenna spectrum used in previous calculations however, indeed mainly excited external modes. The code results therefore predict the β-dependence as to be expected for external modes that are driven unstable by plasma pressure.

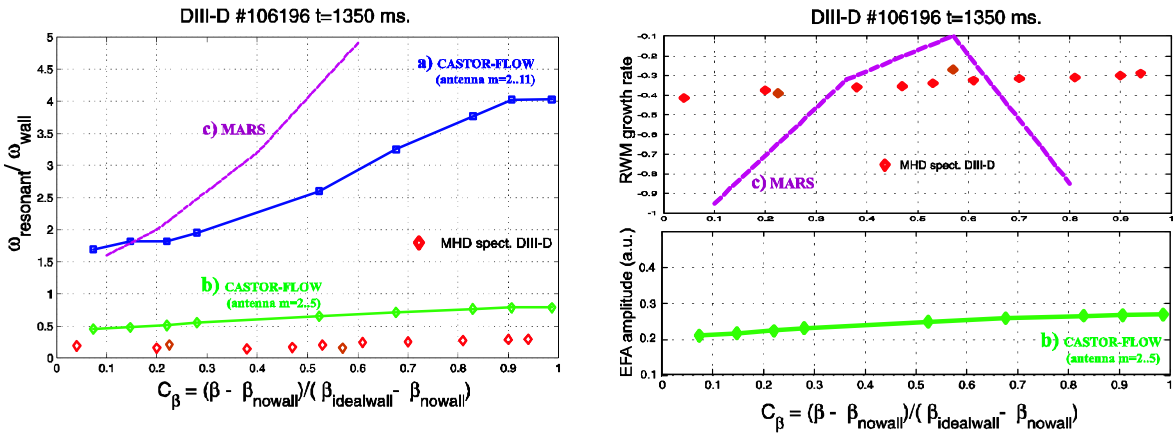

Figure 3. Comparison of the CASTOR-FLOW calculations with experimental results from DIII-D and MARS code results: a) CASTOR-FLOW calculations with a broad poloidal spectrum of the antenna currents: m=2…11 b) CASTOR-FLOW calculations with the experimental poloidal spectrum of the antenna currents: m=2...5 c) MARS code calculations (equilibria are similar but not identical)[8]. Diamonds show results of MHD spectroscopy experiments in DIII-D[10].

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[1] E.Strumberger et. al., Submitted to Nucl.Fusion.
[2] V.Igochine et.al., **31st EPS Conference**, 2004, P-4.129
[3] G.T.A.Huysmans, Phys.Pl., **2**, (1995) 1605
[4] R.Fitzpatrick, Phys.Pl., **9**, (2002) 3459
[5] A.Bondeson et. al., Phys.Fluids B, **4**, (1992) 1889
[6] R.Betti and J.P.Freidberg, Phys.Rev.Let., **74**, (1995) 2949
[7] M.S.Chu et. al., Phys.Pl., **2**, (1995) 2236
[8] H.Reimerdes et. al., Phys.Rev.Let., **93**, 2004, 135002
[9] G.L.Jackson et. al., **30th EPS Conference**, 2003, P-4.47
[10] H.Reimerdes et. al., **31st EPS Conference**, 2004, P-2.184