Modelling the effect of resonant magnetic perturbations on neoclassical tearing modes

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Introduction:

A high achievable normalized beta factor in present days tokamaks is limited by pressure driven instabilities. A good candidate for the latter role is the resistive neoclassical toroidal mode (NTM), whose stabilization becomes compulsory.
On the other hand, external structures surrounding the plasma column, such as the radial feedback coils could easily play the a destabilizing role by generating an error field spectrum of small perturbations that couple with the NTMs and amplify the latter modes, as the no-wall beta limit is approached. This could be the case for the ASDEX-Upgrade (AUG) plasma surrounded by a set of error field generating in-vessel saddle coils [1].
A quasi-analytic model is developed to describe the error field influence on the NTMs, applied to the specific case of the AUG plasma with its B-coils peculiar system.

3D modeling:

- natural flux coordinates of Hamada type
- low inverse aspect ratio approximation
- resistive inhomogeneous thin passive shell
- assumption that the wall and the feedback/error field generating coils and detectors lie on magnetic surfaces

Solving perturbed equations:

- perturbed resistive magnetic island equations
- perturbed ideal plasma momentum equations
- circuit equations in plasma column external structures
- perturbed vacuum equations
- perturbed boundaries equations

Strategy:

- Fourier development, Laplace transformation, Laplace transformed equations solving via partial fraction decomposition, inverse Laplace transformation.

Model Presentation

A quasi-analytic, explicitly time-dependent formula for the NTM perturbed magnetic flux function is obtained [2,3]:

$$\psi_s^{mn}(t) \equiv \frac{1}{\tau_{FKR}^{5/4}}\left\{\frac{A_s^{mn}}{\Gamma(9/4)}t^{5/4} - \frac{\mathrm{i}B_s^{mn}}{n\Omega_{MP}}\left[\frac{t^{1/4}}{\Gamma(1/4)}\left(4+e^{-\mathrm{i}n\Omega_{err}t}E_{3/4}(-\mathrm{i}n\Omega_{err}t)\right) - \frac{e^{-\mathrm{i}n\Omega_{err}t}}{(-\mathrm{i}n\Omega_{err})^{1/4}}\right] - \sum_{p=1}^{6L}\frac{C_{ps}^{mn}}{\tau_p}\left[\frac{t^{1/4}}{\Gamma(1/4)}\left(4+e^{\tau_p t}E_{3/4}(\tau_p t)\right) - \frac{e^{\tau_p t}}{\tau_p^{1/4}}\right]\right\}$$

The delta prime stability index:

$$\Delta'_s(t) = -\frac{2m}{r_s}\left[1-\frac{\psi_{s,ideal}^{mn}(t)}{\psi_s^{mn}(t)}\right]$$

where[2,4]: $$\psi_{s,ideal}^{mn}(t) = A_s^{mn} + B_s^{mn}e^{-\mathrm{i}n\Omega_{err}t} + \sum_{p=1}^{6L}C_{ps}^{mn}e^{\tau_p t}$$

$$t_{FKR} = (\tau_r^{3/5}\tau_a^{2/5}/m^{6/5})[\pi\Gamma(3/4)/\Gamma(1/4)]^{4/5}$$

All the above parameters are analytically derived functions of ideal/resistive plasma, wall, coils, error field (static and rotational) and initial perturbations parameters.

Error field correction

Amplitude scan of a mixed (2,1) error field effect is calculated in figure 2, using the model we proposed. This corresponds to the 33959 AUG discharge (see figure 1) where an error field (EF) having a fixed AC component (400*A* AC amplitude and −10*Hz* frequency) spans different DC amplitudes (*0A,100A,300A,400A*) during its evolution, for a toroidal phase of 0º and a phase difference of 90º. As the AC EF amplitude is switched on, its frequency drops in order to rise again when the DC EF amplitude reaches 100*A*.

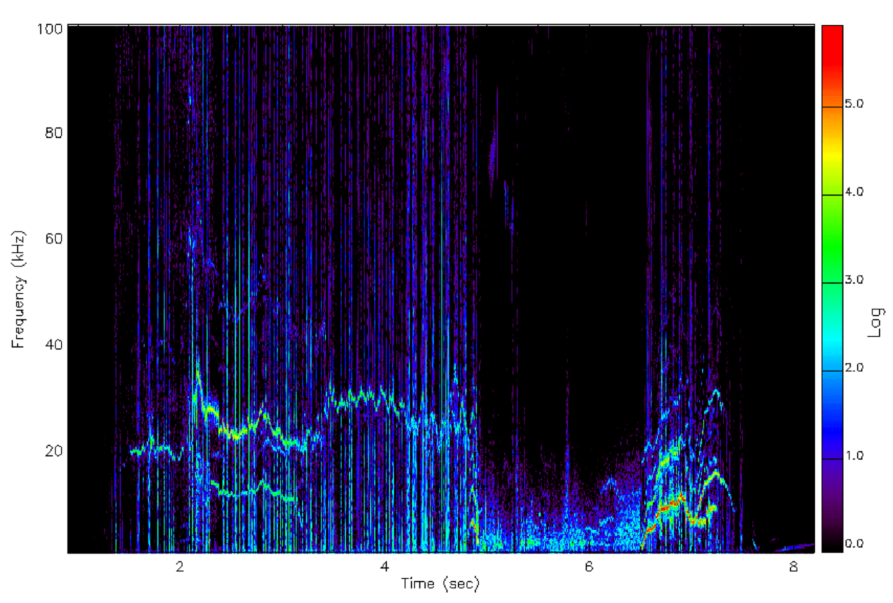

Figure 1: *(2,1) frequency evolution (#33959)*

As it has been reported, here the EF effect has its lower influence, also shown by the calculations. There is no frequency peak during the 300*A* DC regime but within the 400*A* regime the mode locks to the EF and a significant drop of the mode frequency is found.

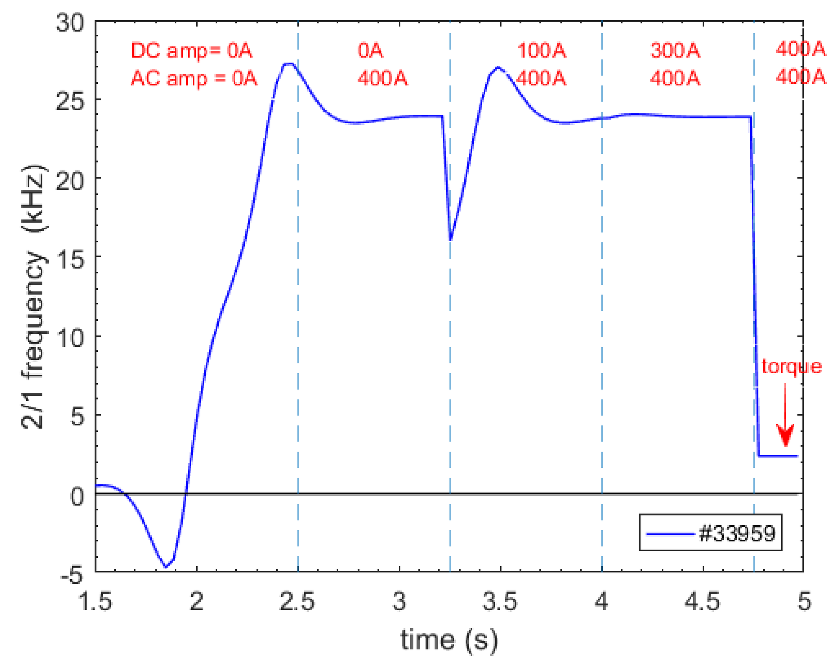

Figure 2: *(2,1) calculated frequency (#33959)*

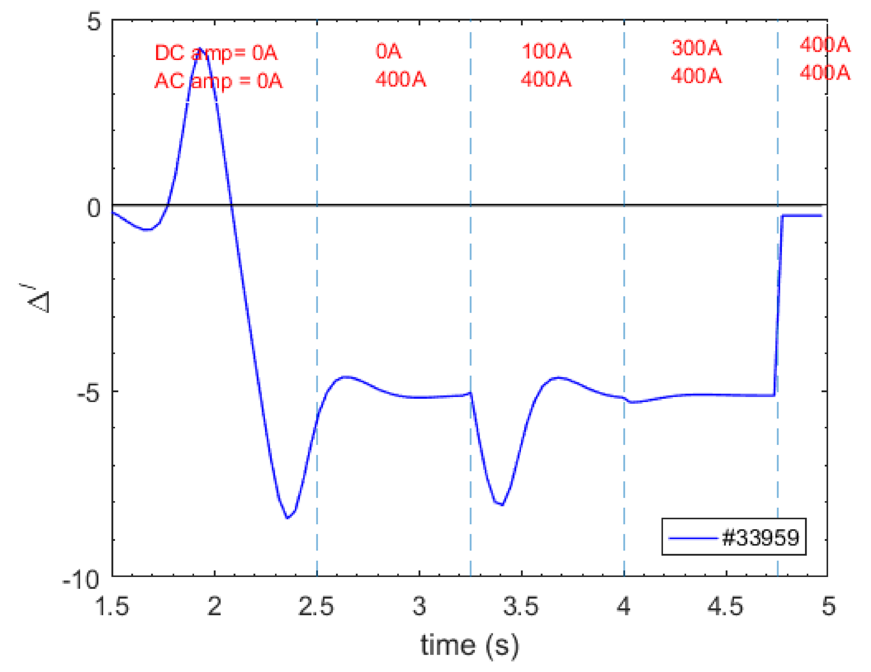

Figure 3: *(2,1) calculated stability index (#33959)*

A caution is necessary. Our model describes the small perturbations evolution relying on the assumption that the equilibrium quantities do not significantly change. A locking phase evolution followed by a massive drop of the plasma rotation cannot be described by a perturbed model. Therefore we have simply decreased the plasma rotation within the 400*A* regime, according to the experimental results, in order to show the calculated frequency drop. However the previous regimes are perfectly eligible to be described by the model. The calculated corresponding stability index is found in figure 3 showing the negative peak of Δ′ as the 100*A* DC regime is attained.

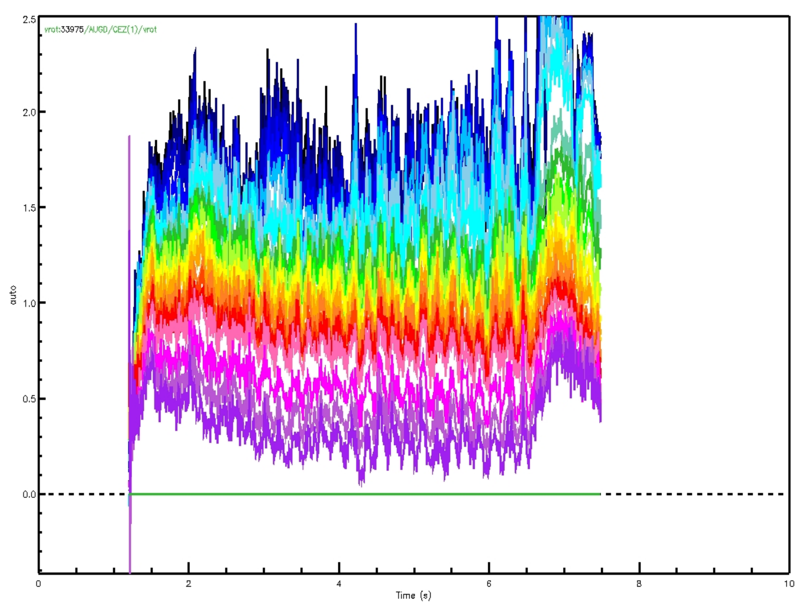
Figure 4: *(2,1) frequency evolution (#33975)*

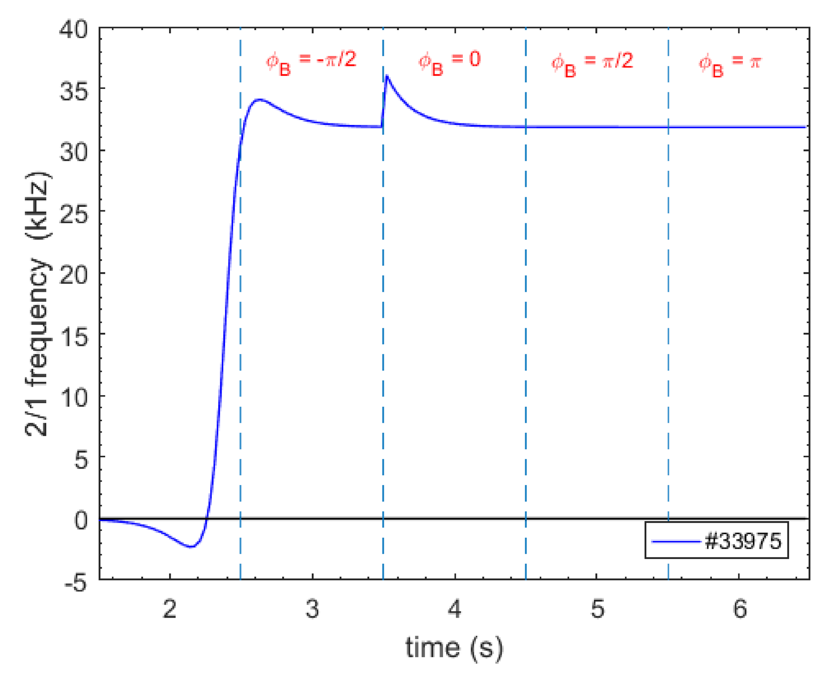

Figure 5: *(2,1) calculated frequency (#33975)*

A similar comparison is performed for the 33975 AUG discharge showing a phase scan of a (2,1) mixed EF effect of 200*A* DC and AC amplitudes and −5*Hz* AC frequency, for different phases (−90º,0º, 90º,180º). The phase difference is 90º. As reported from experimental results, from figure 4, the frequency peak showing the minimum modulation due to EF corresponds to the calculated frequency within the 0º phase regime (see figure 5). The mode frequency locks to the plasma rotation frequency at later times, the latter frequency being kept constant in order the perturbed model to be valid.

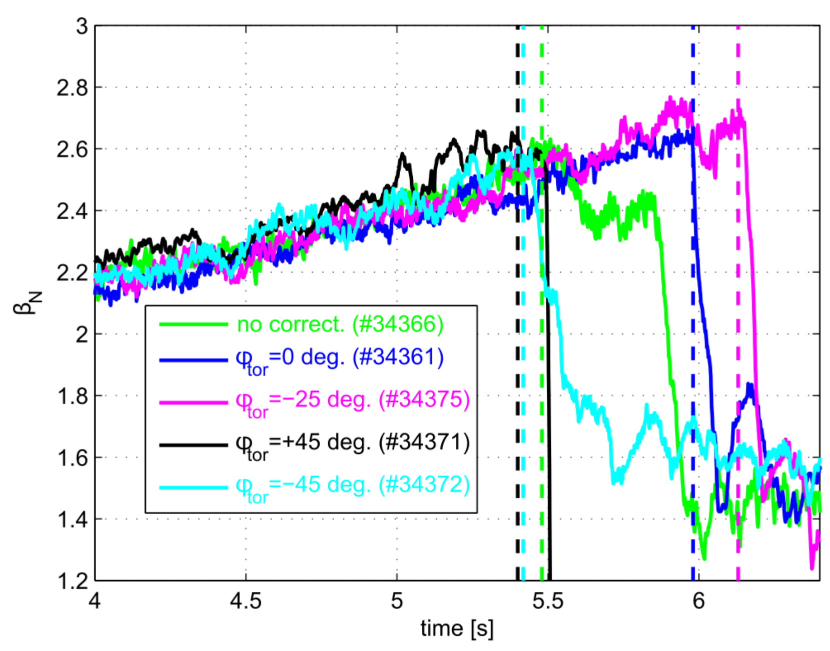

Figure 6: *Evolution of the normalized beta for different toroidal phases (Ref. [5])*

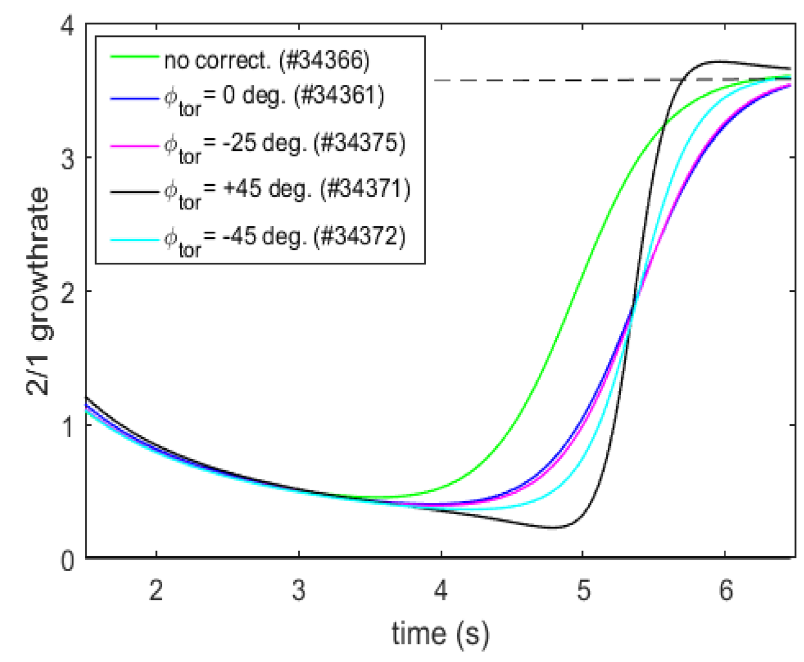

Figure 7: *(2,1) growth rate for different error field configurations*

Experiments related to some AUG discharges (34366, 34361, 34375, 34371 and 34372) showed that the externally applied *n* = 1 EF correction delays the onset of the MHD modes regarding the used toroidal phase [5]. It has been found that for a static EF of 200*A* DC amplitude and phase difference of 90º, the optimal error field correction settings correspond to the 0º.. −25º toroidal phase regime. For reasons stated above, our model is not able to measure the delay of the drop of the normalized beta for different EF correction settings, as in Ref [5] (figure 6). Instead, the growth rate of the mode is calculated. As shown in figure 7, the +45º toroidal phase corresponds to the fastest mode growth rate in order to reach its maximum value, whereas within the 0º..−25º toroidal phase regime the delay of the onset of the mode is maximum. Basically the calculations retrieved the experimental results.

References

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