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# Modeling of the impact of ECCD sweeping on NTM stability in ASDEX-Upgrade

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## Introduction

By reducing the maximum achievable  $\beta$ , Neoclassical tearing modes (NTMs) limit the performances of fusion devices. They can be controlled using Electron Cyclotron Current Drive (ECCD) as demonstrated in many tokamaks [1]. A new method, relying on sweeping ECCD deposition around the estimated position of the mode has been successfully tested on TCV[3] and applied to ASDEX-Upgrade during the 2014 MST-1 campaign [2]. It relies on the idea that the mean effect of the sweeping will still be favorable for the mode reduction, which relaxes the need for precise rational surface location. This allows the development of robust control systems. This paper focuses on the effects of ECCD sweeping across the rational surface on the stability index  $\Delta'$ , in particular to quantify the potential destabilizing effect. The stabilizing role of localized ECCD inside the island is also discussed and preliminary results are presented. The analysis is performed using the 3D full MHD code XTOR-2F [4], which includes a current source term modeling the ECCD in the Ohm's law [10].

## Brief description of the experiment

An example of successful application of the sweeping strategy can be found in AUG pulse #30594 (figure 1 of [2]). A (3,2)-NTM is triggered by rising NBI power up to 17 MW. Once the mode is detected, the NBI power is reduced to 10 MW. The plasma current is about 1 MA, and  $\beta_N \approx 1.8$ . A first gyrotron is switched on with a power of about 750 kW. Mirrors orientations are then modified such that the current deposition radial location oscillates around the rational surface. This ensure that current is periodically deposited inside O-Point. A second gyrotron, and then a third gyrotron are switched on, leading to the mode disappearance. The sweeping strategy hence proves its capability to successfully suppress an NTM.

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<sup>†</sup>See <http://www.euro-fusionscipub.org/mst1>.

## Physical model and equilibrium with neoclassical physics

The nonlinear MHD code XTOR-2F [4] solves the two fluid 3D MHD equations in a torus. The neoclassical effects are implemented via the neoclassical viscous stress tensors [5]. The current induced by the RF source implementation is detailed in [10]. We use an equilibrium issued from AUG pulse #30594 at  $t = 4.0s$ , that is after a (3,2)-NTM has appeared on the  $q = 3/2$ -surface, at  $\rho \approx 0.55$ , where  $\rho$  is the normalized poloidal flux. For simplicity, the shape of the separatrix is modified to be up-down symmetric. Pressure and density profiles are fitted from AUG pulse #30594 using IDA (*Integrated Data Analysis*) at  $t = 4.0s$ . The central density is  $n_i(0) = 9.4 \times 10^{19} \text{ m}^{-3}$ , the magnetic field on the axis is  $B_0 = 2.5 \text{ T}$  and the central temperature  $T_e^0 \approx 3.6 \text{ keV}$ . At equilibrium, the bootstrap current computed by XTOR is in good agreement with predictions of the Sauter's formula [6] (figure 1).

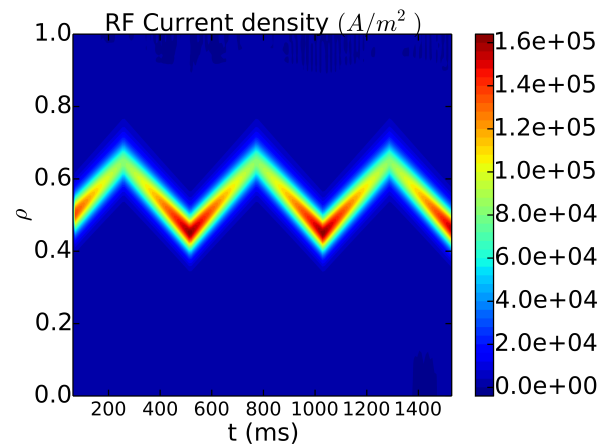
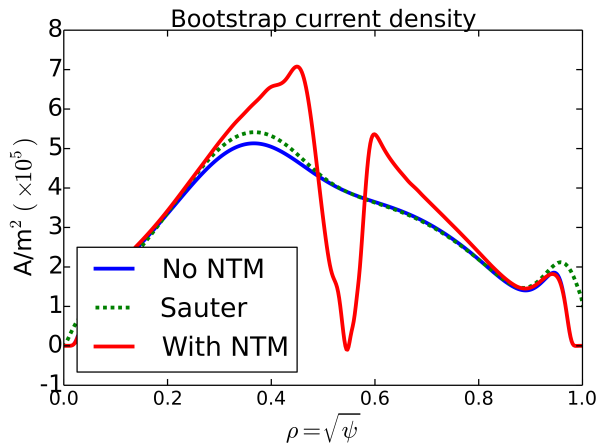


Figure 1: Bootstrap current density averaged over flux surfaces, as obtained with XTOR-2F and using Sauter's formula.

Figure 2: Evolution of the RF Current density

## Effect of ECCD sweeping on the linear stability

One of the concern arising from the sweeping procedure is that it could have deleterious effects on stability through equilibrium modifications, by increasing the mode stability index  $\Delta'$  when the current deposition is off the rational surface [7]. In the following, we consider the evolution of the stability index  $\Delta'_{(3,2)}$  of the (3,2) mode for a current injection (12 kA, corresponding to approximately 3 gyrotrons) at different locations around the rational surface, using the one-fluid MHD model. The radial width of the current source has been determined using data from TORBEAM[11] at  $t = 4.0 \text{ s}$ . As expected, we retrieve a stabilizing effect for  $\rho_{ECCD} \geq \rho_{q=3/2}$ , and a destabilizing one otherwise. This is plotted on figure 3 where the evolution of  $\Delta'_{(3,2)}$  during a triangular sweep around the surface  $q = 3/2$  is

also plotted, with the experimental frequency of 2 Hz and also with a frequency of 4 Hz. One can see that the sweeping process induces a hysteresis-like modification of the equilibrium. The amplitude of the  $\Delta'_{(3,2)}$  modification, is not enough to destabilize the mode, as it is compensated by curvature stabilization, whose value is approximately 23, following [9]. It can also be noted that increasing the sweeping frequency reduces the deleterious effects on equilibrium, as it gives less time for the current to locally modify the equilibrium.

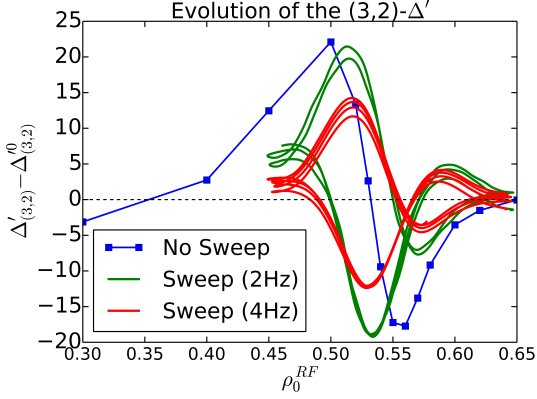


Figure 3: Effect of ECCD on  $\Delta'_{(3,2)}$ .

We introduce a simple analytical model to reproduce this result, described in (equation 1), where  $T$  is a triangle wave function, centered on  $\rho = 0.55$ , with a total amplitude of 0.2, a frequency  $f$  and  $\Delta'_s(\rho_{RF})$  the final value of  $\Delta'_{(3,2)}$  for a source at fixed position  $\rho_{RF}$ .

$$\begin{cases} \frac{\partial \Delta'}{\partial t} = \frac{1}{\tau} (\Delta'_s(\rho_{RF}(t)) - \Delta') \\ \rho_{RF}(t) = T(0.55, f, 0.2) \end{cases} \quad (1)$$

This model is able to capture the hysteresis phenomenon, as shown on figure 4. We retrieve the decrease of the impact on equilibrium as the frequency is increased (figure 5). (It should be noted that in experiments, this frequency is limited by the time necessary for the mirrors to move to their prescribed positions). To conclude, the effect of sweeping on linear stability is not negligible, although not critical in the present experiment.

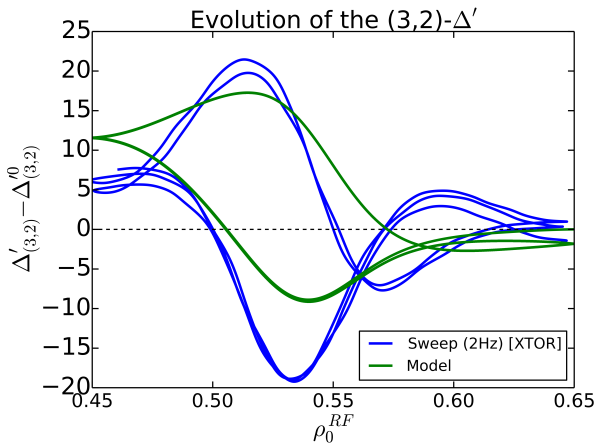


Figure 4: Evolution of  $\Delta'_{(3,2)}$  procuded by the analytical model (equation 1) and XTOR.

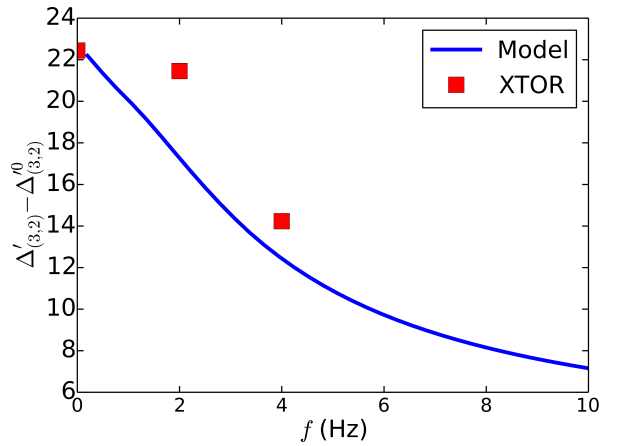


Figure 5: Variation of the maximum reached  $\Delta'_{(3,2)}$  for different frequencies of the sweeping.

## Toward NTM stabilization by ECCD Current

The previous section shows that the most important effects for the island stabilization are the 3D effects [8]. We consider the situation where an NTM is present during the ECCD application. Simulations are carried out using a two-fluids neoclassical model. A (3,2)-NTM is driven by inducing a current perturbation on the rational surface  $q = 3/2$ , using the current source term. Once the island is properly setup and the bootstrap current nullified inside (figure 1), we proceed to drive current on the rational surface  $q = 3/2$ , using a 1D source term. In these preliminary simulations, we have a large ergodic region in the vicinity of the magnetic island. This leads to a large broadening of the RF-driven current density (as shown on figure 6), reducing the efficiency  $\eta_{RF}$  of the control.

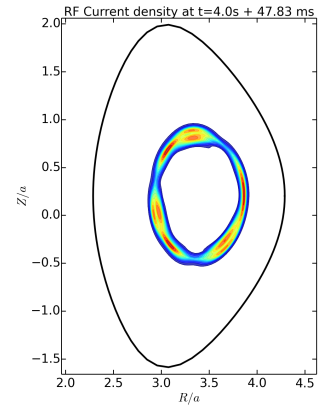


Figure 6: Distribution of the RF Current density.

## Conclusion

In this work, the impact on the sweeping strategy on the linear stability of the (3,2)-mode has been investigated. It is shown that the sweeping method can, when all the gyrotrons are switched on, have a significantly impact on the linear stability. It is also shown that the sweeping process induces an hysteresis-like modification of the equilibrium, due to the finite-timescale needed to perturb the equilibrium. Increasing the sweep frequency helps mitigating these effects. The work regarding the (3,2)-NTM stabilization has been initiated using the full bi-fluid and neoclassical MHD mode.

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