# Avoidance of m=2, n=1 tearing mode wall-locking by torque-balance control with magnetic feedback in DIII-D and RFX-mod

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Recent experiments performed in DIII-D [1] and RFX-mod operated as a tokamak [2] have demonstrated that magnetic feedback realized by active saddle coils is able to push a wall locked $m$=2, $n$=1 tearing mode (TM) into slow rotation with frequency of the order of several tens of Hertz. The result is not obvious, given the many differences of the two experiments both in terms of layout and plasma condition. In DIII-D ($R_0$=1.6m, $a$≈0.6m) diverted, D-shaped, high-β plasmas, controlled by coils placed inside the 5ms time-constant vacuum vessel have been performed. Instead, in RFX-mod ($R_0$=2m, $a$=0.459m) we realized circular cross-section, limiter, ohmic discharges with low edge safety factor, $2<q(a)<3$, feedback controlled by active coils placed outside the 100ms time-constant copper shell. As shown in [3] the feedback-induced frequencies can be interpreted as an equilibrium condition in which the viscous torque due to the plasma flow balances the electromagnetic torque developed by the interaction between TM and the external passive and active conductive structures. For mode amplitudes above the wall-locking threshold, electromagnetic torque $T_{EM}$ is the dominant effect (see figure A.1 of [3]), and the feedback-induced frequencies are approximately the solutions of the equation $T_{EM}(\omega)=0$, satisfying the stability requirement $\partial T_{EM}/\partial\omega<0$. A cubic equation for $\omega$ is obtained, as shown in [1] on the basis of a model which describes the coupling between TM and the conductive structures in terms of mutual inductances [4]. A similar equation can be derived using the cylindrical Newcomb's model described in the appendix of [3], considering one single wall, and radial field sensors placed, for the sake of simplicity, on it. A wall-locked solution $\omega$=0 is selected for feedback proportional gain $K$ ($K$<0) such that $K/K_{crit}$<1. Here $K_{crit}$<0 is a critical value, which assumes different expressions depending on the active coils location with respect to the wall (out-shell for RFX-mod, in-vessel for DIII-D). It depends on the ratio $\tau_w/\Delta t$ between the wall time-constant and the global delay of the feedback chain. For $K/K_{crit}$>1 two opposite feedback frequencies

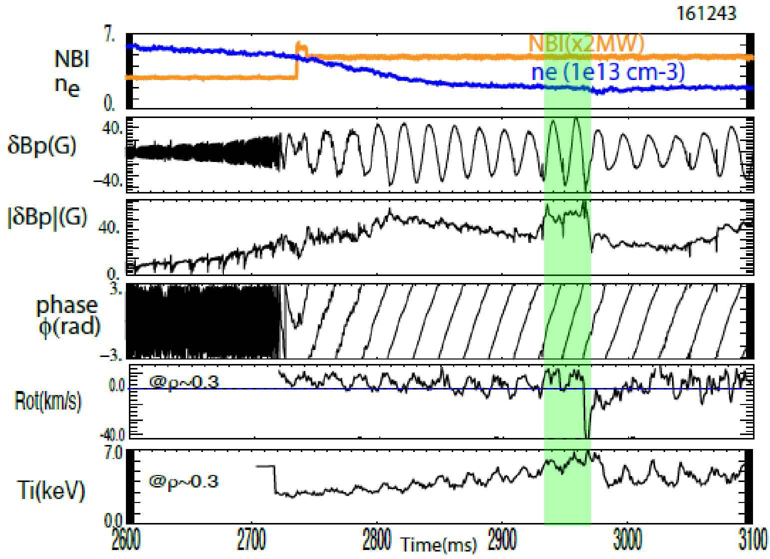


**Fig. 1**. Example of $m$=2, $n$=1 TM control in DIII-D. The green vertical band indicates the occurrence of an internal reconnection event.

$\omega = \pm\sqrt{K/K_{crit} - 1}\,/\Delta t$ are obtained, which amount to some tens of Hertz for both RFX-mod and DIII-D, as experimentally observed. In DIII-D a control variant with $K$ complex, corresponding to a small phase shift, is routinely used, since it increases the stability of the rotations [1]. With complex gains the previous formula assumes a slightly different form [1].

Since such a simple and fundamental model unifies the interpretation in two very different configurations, it can be concluded that the phenomenon does not depend on many details of plasma parameters and is robust and reproducible. An example of the resiliency of this process against unexpected events such as a major internal reconnection is presented in Figure 1 for DIII-D. Here, the feedback induced rotation at about 50Hz is established (fourth panel) as soon as the TM amplitude increases (second and third panel, where the $n$=1 harmonic is plotted; a dominant $m$=2 component is identified) to a level that would lead to wall-locking without control. This rotation produces modulations in the ion velocity signal (fifth panel) and temperature (sixth panel). The density reduction from $4\times10^{13}$cm$^{-3}$ to $1.5\times10^{13}$cm$^{-3}$ (first panel) induces an increase of the central ion temperature from 4keV to 7keV (sixth panel). The consequent rise of the core pressure gradient produces an increase of the MHD activity, highlighted by the green band, culminating in a minor disruption at t=2965ms. Internal MHD events such this can cause significant modification of localized radial electric field with important impact on plasma flow velocity. In fact, a significant reversal of the velocity, concomitant with the temperature drop, follows the reconnection event (the time delay of the measured $T_i$ drop with respect to the rotation negative spike is presumably related to the toroidal asymmetry of the fast collapse process). In spite of this, the feedback induced frequency remains almost unchanged.

There is a crucial difference between TM rotations induced by feedback and those produced by locking the mode to a feed-forward perturbation of given amplitude and frequency. Generally speaking, in the former case the phase difference with respect to the external perturbation stabilizes the amplitude, so the mode saturation level is reduced. Instead, in the latter case the phase difference is destabilizing [5]. However, even the feed-forward induced rotation can mitigate the mode amplitude owing to the screening effect of the passive conductive structure [5] (at least a vacuum vessel is present). Though an experimental comparison of the two techniques for control of wall-locked TM in the same experiment is lacking (in [6] both methods are examined, but they are applied to fast rotating $m$=2, $n$=1), simulations with the RFXlocking code [2] indicate a superiority of the feedback, at least with the external active coils of the RFX-mod layout so far considered. An example is shown in figure 2 for an equilibrium where a growing amplitude $m$=2, $n$=1 TM tends to wall-lock. The feedback is active up to 0.2s, and afterwards it is turned off imposing a feed-forward $m$=2, $n$=1 current on the active coils with amplitude and frequency respectively factors 4 and 0.5 of the values reached during the previous feedback phase. Adjustment of this kind is necessary to sustain feed-forward rotations. Rutherford's equation for the island width is considered only after 0.06s, whereas the width is kept constant to very low level during the first part of the simulation, to allow the mode frequency to settle on the natural value (some kHz). The asymptotic island width of the feed-forward phase, met after the damping of the oscillations, is slightly smaller than the saturation value 0.146m that would be reached in the absence of any control (not shown in the plot), but significantly larger than the value obtained with feedback. One may object that using feed-forward the TM frequency can be forced to a desired value, whereas under feedback this is not possible. However, relaxing the

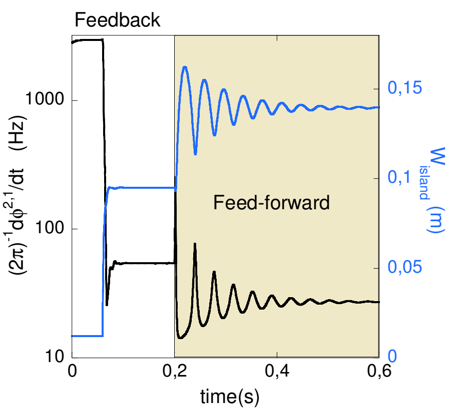


**Fig.2**. RFXlocking simulation of $m$=2, $n$=1 control, showing mode frequency (black; log-scale) and island width (blue; a=0.459).

constraint of zeroing the feedback variable with the addition of a small-amplitude rotating reference it is possible to select the desired TM frequency, in a range of reasonable requirements. This variant of the feedback scheme is shown in Figure 3 for a RFX-mod discharge. Schematically, the feedback law is $I^{2,1}_{coil} = K\left[b^{2,1}_r(r_{sens}) - b_{ref}\exp(i\omega_{ref}t)\right]$. In this example the TM slows down from the fast natural frequency (some kHz) such as to become visible on the feedback sensors, which are located inside the shell, but are screened by the innermost 3ms time-constant vacuum-vessel, only in the time window between 0.2s and 0.45s, where a significant amplitude is detected (plot a). As shown by plot b, during this interval feedback rotation is established with $\omega_{ref}/2\pi$=25Hz imposed by the small non-zero reference ($b_{ref}$=1G). Outside this interval no plasma mode is seen, and sensors detect only the rotating reference: the radial field extrapolated at the plasma radius becomes noisy as the toroidal field signal, which is used to compute it. The transitions from the fast to the feedback rotation at t≈0.2s and its inverse at t≈0.45s are arguably due to equilibrium changes not measurable with the present RFX-mod diagnostics.

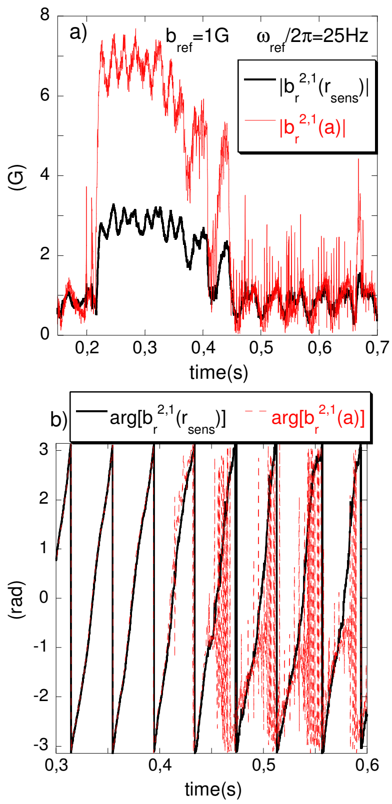


**Fig.3** Example of $m$=2, $n$=1 TM feedback control with non-zero reference at 25Hz in RFX-mod. We show the radial field harmonic at the sensor radius (black), and the extrapolation at the plasma surface (red), computed with the inclusion of the toroidal field signal. Plot a) refers to the amplitude, plot b) to the phase.

In conclusion these experiments performed at DIII-D and RFX-mod have demonstrated that magnetic feedback is a robust technique to avoid wall-locking of the $m$=2, $n$=1 tearing mode, that can be implemented, in principle, in any tokamak device.

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*Work supported in part by the U.S. Department of Energy under DE-AC02-09CH11466, DE-FC02-04ER54698, DE-FG02-04ER54761, DE-SC0008520, and DE-FG02-08ER85195.