

Real-time control of neoclassical tearing modes and its integration with multiple controllers in the TCV Tokamak

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Introduction

For long-pulse scenarios in large tokamaks, supervision of the plasma discharge evolution is increasingly important and requires efficient actuator management (AM) [1]. Because of its flexibility, electron cyclotron resonance heating/current drive (ECRH/ECCD) is a good candidate for AM [2]. Among the several physics phenomena and parameters that can be controlled by ECRH/ECCD, neoclassical tearing modes (NTMs) can degrade plasma confinement and lead to disruptions [3], causing a major concern for ITER; and control of plasma profiles is required to achieve advanced tokamak operations in ITER and future reactors [1]. With a preliminary design of the AM module, real-time integrated control of NTMs, beta (the ratio of plasma pressure to magnetic pressure) and model-estimated safety factor (q) profiles has been tested experimentally in TCV for the first time.

Much effort has also been devoted to the understanding of NTM physics to achieve better control. In [4, 5] it was shown that more central co-ECCD (i.e. current driven in the same direction as the plasma current I_P) power is favorable to triggering NTMs. Recent NTM experiments with central co-ECCD show that a decrease of density (resulting in an increase in the driven current I_{CD}), counter-intuitively, makes it harder to trigger the modes - there appears to be a specific density range within which NTMs can be destabilized. This may arguably be related to the modification of global q profiles and thus the stability of the conventional tearing mode.

Integrated control of NTMs, beta values and model-estimated q profiles

The integrated control experiments used the digital control system of TCV and two clusters of second harmonic X-mode (X2) EC actuators: cluster A (P_A) which supplies one EC launcher

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(L1) and cluster B (P_B) which consists of two launchers (L4 and L6). L1 was set to be in counter-ECCD while L4 and L6 were used in co-ECCD.

The control scheme used follows the control architecture proposed in [6] and [7], as shown in Fig. 1. The central decision layer sets control priorities - NTM control takes the highest priority once a mode is detected, but with the additional constraint that P_A is always reserved for beta and q-profile control. Following the priorities, the high-level AM layer allocates the three EC actuators to different control tasks in real-time; the basic controller layer contains a NTM controller and a multivariable controller (hereinafter referred to as profile controller) that controls beta and q profiles simultaneously. The profile controller was designed by an adaptive control method [8] and the controller test environment is described in [9]. The low-level AM layer for now simply combines actuator inputs from the NTM and profile controller and those from feedforward requests and can be extended in the future with the scheme proposed in [7].

The results of two integrated control tests are shown in Figs. 2 and 3, where in both cases I_P was kept constant at 110 kA. Note that due to the absence of internal current density measurements in TCV, the q profiles used in these tests are estimations provided by RAPTOR [10]. In the first experiment (#54857), EC power was switched on at 0.5s, following the feedforward power traces and deposition location (at the plasma center, as shown in the fourth panel). The real-time integrated control started at 0.7s and both beta and q-profile references (the second and third panels) were followed very well. A 2/1 NTM was triggered at about 0.85s and a real-time NTM trigger [11] was sent to the central decision layer which gave priority to NTM control.

With full access to P_B , the NTM controller first requests one launcher (L6) to move towards the mode location ($q=2$ surface) with its maximum power (500kW); once the mode stays longer than a given time, as shown in the fourth panel, a second launcher (L4) is moved to the mode location as well; losing control of all the co-ECCD power (i.e. P_B), the profile controller cannot follow the q-profile requests. NTM was fully stabilized with two launchers at about 1.41s, but then we lost P_B due to technical issues and beta requests could not be satisfied.

#56701 (Fig. 3) is a complementary test to #54857 and follows a similar control scheme, except that a further upgrade on AM was done - P_B is reduced to its minimum during the movement of the launcher mirrors to minimize the perturbations exerted on the profile controller. A 2/1 NTM was triggered at about 0.81s, then L6 moved and fully stabilized the mode. As shown

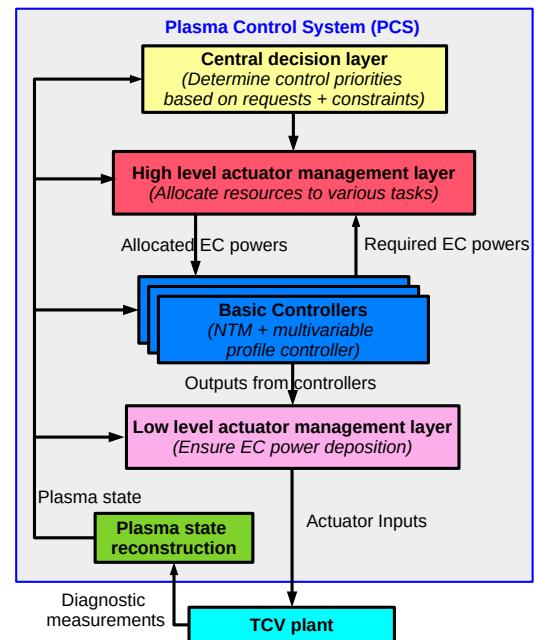


Figure 1: The control scheme used in the integrated control experiments

by the green and red curves in the first panel, P_B was reduced to 200kW during the varying of beam deposition locations. A second 2/1 NTM was triggered at about 1.67s and two launchers were moved to mode location one by one, but not enough time was left for full stabilization.

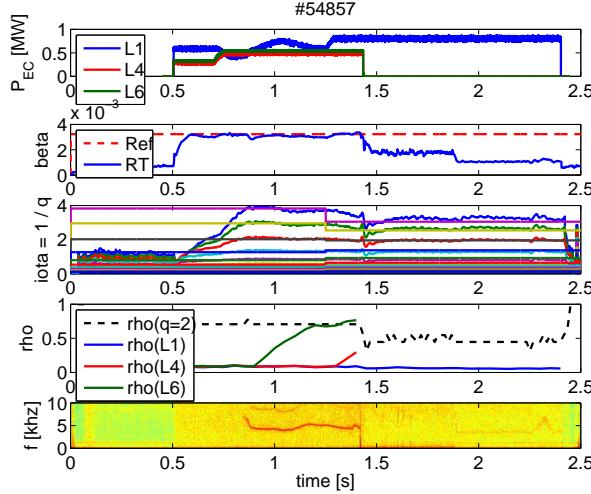


Figure 2: First integrated NTM and profile control test in TCV

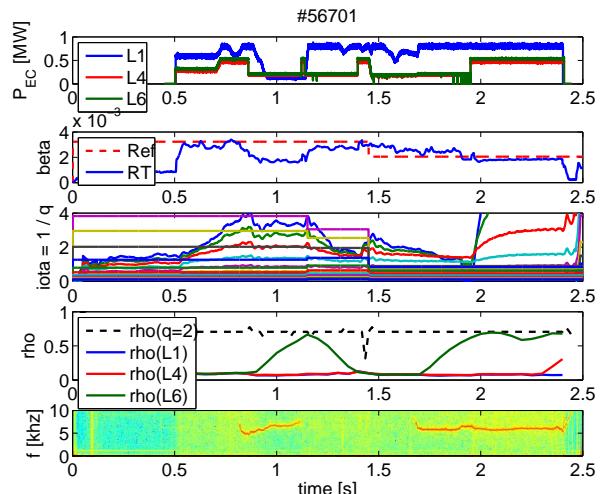


Figure 3: Integrated control test with upgraded AM module

Density effects on the destabilization of NTMs

In the NTM destabilization experiments, 1 MW of co-ECCD power was deposited at the plasma center to trigger the modes essentially through a global change of the q profiles. With a density level well below the cut-off density of X2 waves ($4 \cdot 10^{19} m^{-3}$) and high EC absorption rate, it is found that NTMs can only be triggered within a certain density range - too high or too low density will hinder the triggering. Fig. 4 summarizes 50 stationary instances taken from 33 TCV tests and shows the possibility of triggering NTMs under different density levels, where all the cases have similar plasma shape and position. It shows that NTMs can be triggered with a line-averaged density (n_{el}) ranging from $1.45 \cdot 10^{19} m^{-3}$ to $2.05 \cdot 10^{19} m^{-3}$ while no NTM triggering has been found with n_{el} below $1.45 \cdot 10^{19} m^{-3}$ or above $2.05 \cdot 10^{19} m^{-3}$ so far.

To interpret this phenomenon, three different density cases are analyzed - #56122 with a n_{el} of $2.55 \cdot 10^{19} m^{-3}$, #56124 of $1.84 \cdot 10^{19} m^{-3}$ and #54653 of $1.40 \cdot 10^{19} m^{-3}$. Both ray tracing and stationary current balance calculations show that I_{CD} is respectively 40, 45 and 60kA in #56122, #56124 and #54653, but NTM was only triggered in the moderate density and I_{CD} case (#56124). This seems to contradict earlier findings that higher co-ECCD power and lower I_P (thus higher I_{CD}/I_P) are favorable for NTM triggering [5].

A possible explanation is that the classical tearing term (Δ'), driven by the unstable q profiles, in the Modified Rutherford Equation (MRE) [3] is different under different density levels and can be positive in specific cases, which will cause the growth of a conventional tearing

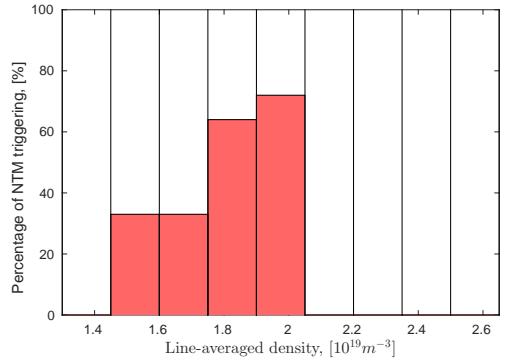


Figure 4: Possibility of NTM destabilization under different density levels

mode, thus providing seed islands and leading to the growth of NTMs [4, 12]. Note that co-ECCD was deposited in the center (far away from $q=2$ surface) to trigger the mode and we have tested that we are unable to trigger NTMs with local CD near $q=2$, so the mode should result from the global change of q profile and thus Δ' . The q profiles (computed by ASTRA [13]) of the three cases are compared, as shown in Fig. 5. The radial locations of the $q=2$ surface are indicated by the vertical lines and the local q gradients (i.e. $dq/d\rho$) are also listed. Different cases have different q profiles, which in specific cases may lead to a positive Δ' and provide large enough seed islands for NTMs. Note that the central q values are smaller than 1, which indicates the occurrence of sawteeth (ST), but the high q values near the edge and soft X-ray measurements indicate that these ST are small. Actually [14] shows that only under delicate settings can ST crashes be large enough to trigger NTMs in the L-mode scenarios of TCV.

Summary

Preliminary integrated control of NTMs, beta and model-estimated q profiles has been demonstrated experimentally in TCV for the first time. An upgrade of the supervision layer is foreseen. Dedicated NTM tests show that density affects the triggering of NTMs through global q profile modifications with central co-ECCD - too low or too high density will hinder the triggering. More detailed simulations are ongoing to further clarify these effects.

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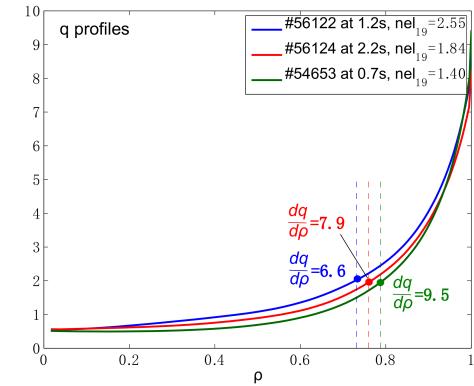


Figure 5: The comparison of q profiles under different density levels