NTM stabilization experiments at ASDEX Upgrade

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Introduction

Neoclassical Tearing Modes (NTMs) limit the achievable normalized beta, which is one of the most important fusion performance figures. A well-established method for affecting and controlling NTMs is the deposition of ECCD inside the magnetic island O-point for stabilization [1]. At ASDEX Upgrade, the project dealing with real-time NTM control has matured and several approaches have been investigated to utilize ECCD as the means to counteract and stabilize the performance limiting NTMs.

Experimental setup

The standard NTM scenario runs with a plasma current of 1 MA at a toroidal field (on axis) of ~ 2.6 T and up to 6 neutral heating beams of 2.5 MW input power each. The divertor is cooled using nitrogen seeding, which also improves confinement [2] and thus helps raising the beta so that NTMs can get triggered. Line averaged densities range between $6.5\cdot10^{19}$ and $8.0\cdot10^{19}$ m^{-2} in the flattop phase of these experiments (after reducing NBI heating to 12.5, 10 or 7.5 MW, which depends on the experimental goal). The maximum available ECRH power overall is about 4 MW for 2 seconds, and 2.4 MW for the remainder of the ~ 7 seconds long flattop phase. Only the (up to 3 available) long pulse gyrotrons (~ 800 kW each) are connected to launchers that allow real-time steering. Moreover, at least 1 MW of ECRH power always needs to be centrally deposited in order to avoid impurity peaking and thus strong radiative losses, which change the current profile such that NTMs may disappear also without external current drive. This typically resulted in only 2 gyrotrons being available exclusively for mode control. Sometimes also technical boundary conditions preclude the use of an otherwise present gyrotron.

Controlled NTM stabilization

As one of the major results from the NTM stabilization project, the controlled stabilization of a 3/2 neoclassical tearing mode using ECCD was successfully demonstrated in several discharges. Figure 1 shows a discharge where a 3/2 NTM was stabilized using one deposition-controlled gyrotron (740 kW). Another gyrotron (600 kW) with fixed launcher angles deposits additional co-current at half radius during the same time. The 3/2 mode appears at t = 1.2 s and persists throughout the high heating phase, growing in size after 2.6 s in stationary conditions while the controlled ECCD launcher takes aim. At t = 3.0 s ECCD power (> 1.3 MW) is switched on. The mode responds with a rapid amplitude decrease and disappears after about 300 ms. Normalized β subsequently recovers and reaches about 2.1, which is

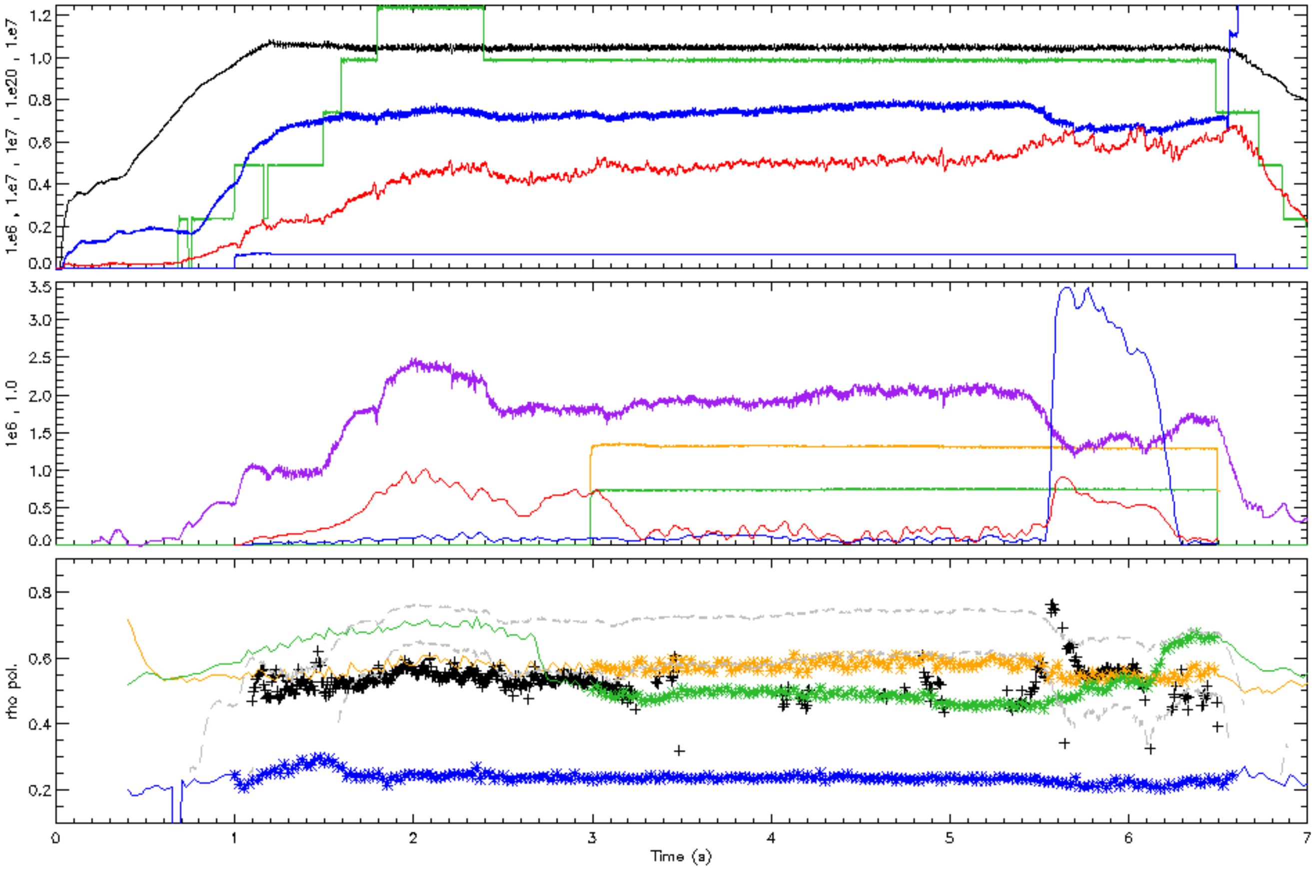

Figure 1: ***Controlled stabilization of 3/2 and 2/1 NTM using one steered launcher (green) (#29672)*** *Upper plot: plasma current (black), plasma density (blue), NBI (green) & central ECRH (blue) heating power [MW] and total radiation (red) versus time. Middle plot: mode amplitude (odd toroidal mode number blue, even t. m. n. red), normalized plasma beta (purple) and off-axis ECCD gyrotron power (green/ orange). Lower plot with normalized poloidal flux in y-direction versus time: radial location of the 3/2 NTM as determined using ECE and Mirnov correlation (black), ECCD deposition aim (green/orange lines), ECCD power deposition (blue, green and orange symbols) q=2/1 and q=3/2 rational surfaces as determined by the real-time equilibrium (dashed grey lines)*

~10% higher than before ECCD was applied. After 2 s, where only a 4/3 mode is present, a 2/1 NTM is triggered, which prompts the controller to switch targets, eventually leading also to the stabilization of the 2/1 NTM. While – due to radiation increase and beta degradation – it cannot be claimed that the 2/1 NTM was stabilized purely due to the applied ECCD, the controller response still demonstrates that our chosen control method knows no fundamental difference between 3/2 and 2/1 islands as long as deposition control can reach both rational surfaces. The scheme is capable of dealing simultaneously with multiple islands as long as enough power on independently controlled launchers is available.

Discharge #29682 illustrates a case where a single gyrotron clearly wasn't sufficient to stabilize the NTM, which was triggered at a $\beta_N > 2.5$ (t = 2.0s) and sustained stationary at $\beta_N \sim 2$. The addition of the second ECCD beam, however, clearly suffices, eventually bringing β_N back up to 2.3. Due to the limited number of deposition-controllable gyrotrons, one of the three available ones was used both for central heating (before 4.0 s) and for mode control (after 4.0 s). Such a dynamic change of priority is foreseen to be more routinely used for discharge control in future experiments. In that discharge (figure 2), deposition control of the orange gyrotron was activated at t = 2.5s. Power is switched on at t = 3.0s, with its deposition on target, leading to a small reduction of the mode amplitude and marginal beta recovery. Immediately after increasing the ECCD power there by means of the second gyrotron (green) to more than 1.4 MW, strong mode amplitude reduction sets in and, subsequently, after the mode disappears, beta can be recovered briefly to values above 2.2. When the green gyrotron changes its deposition (the orange one had reached its launcher angle safety limit and thus couldn't follow) to the newly detected 4/3 NTM position and ECCD at the q=1.5 surface reduces to less than 1 MW, the 3/2 NTM grows back. In response, the controller returns the green gyrotron to the 3/2 surface, but the orange one fails and power of the remaining gyrotron (600 kW) is not sufficient to stabilize the island. False positive NTM detections (black symbols without mode present) are often scattered with short times between conflicting values and hence “filtered” by the longer response time of the mirror drives. At even higher flattop beta of 2.5, which we achieved using 12.5 MW NBI, we haven't yet been able to

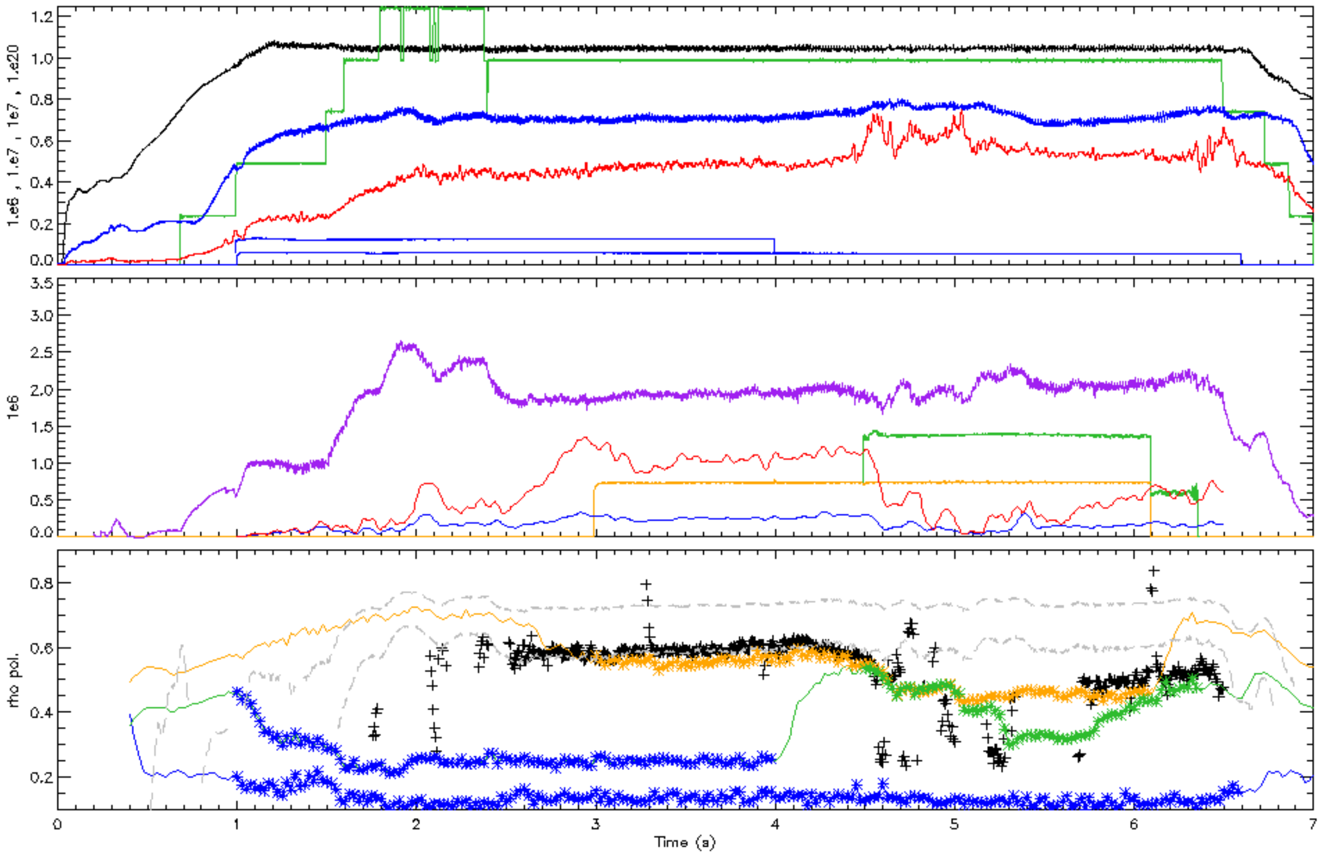

*Figure 2: **NTM stabilization using 2 gyrotrons in succession (#29682)** [Legend like figure 1]*

stabilize the 3/2 NTM in the same manner (using $P_{ECCD} < 1.4$ MW).

In addition to the presented strategy, which applies maximum available ECCD power to the exact NTM location inferred from other sources, alternative control strategies are explored. The so-called "incremental search" technique does not require the exact location of the island, instead information about rational surfaces from the real-time equilibrium is used to steer the ECCD towards a detected mode until a response in mode amplitude is registered. Then, the deposition is adjusted in small steps based on equilibrium and amplitude changes with the ultimate goal to minimize the mode amplitude. This method has also successfully demonstrated 3/2 island suppression using two gyrotrons [3].

Additional results from NTM control experiments

Only the co-current drive inside an NTM acts stabilizing. Current driven outside the island can have a destabilizing effect (in one experiment, we even inadvertently supported the triggering of a 2/1 NTM by a slow co-ECCD deposition scan starting just outside the q=2 surface). Therefore, modulated ECCD deposited mainly in the O-point is known to be favorable for stabilization, especially when the ECCD deposition width significantly exceeds the marginal island width [4]. The actual scenario with the resonance through the magnetic axis doesn't allow the widening of the beam to relevantly sized deposition profiles [5]. Therefore, the ECCD always acts stabilizing independent of the chosen phase relative to the O-point (0°, 180°). Still we find the 0° phasing to be more efficient than the 180° phasing, which deposits mainly in the X-point region and hence at least partially outside the island.

While the stabilizing effect of ECCD has been known for a long time and – in fact – is the main exploited phenomenon to achieve the presented results, NTMs are still an active field of research and hence we also note one parasitically obtained observation. It has been seen that under certain – until now unexplained – circumstances, the signature feature of NTMs (a strong magnetic fluctuation at approximately the plasma rotation frequency times the toroidal mode number of the island) may develop sidebands with a distance to the main frequency of about 1-3 kHz when the NTM frequency is about 20-30 kHz. Those appear strictly symmetric in the Mirnov coils, sometimes even showing harmonics (2nd and 3rd sideband), however, soft X-ray data, which also "sees" a rotating NTM at the same laboratory-frame frequency as Mirnov, oftentimes shows asymmetries in the sidebands and even reductions in the "main" frequency's power such that central and sideband signals are comparable.

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[2] J. Schweinzer et al., "Confinement of 'improved H-modes' … with nitrogen seeding", NF 51, 11 (2011), 113003

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[4] M. Maraschek et al., Enhancement of the Stabilization Efficiency of Neoclassical…", Phys.Rev.Lett. 98, 025005 (2007)

[5] J. Stober et al., "ECRH on ASDEX Upgrade … plasma physics results", EC-16, Sanya, China, Apr. 2010