# Real-time magnetic equilibria for pre-emptive NTM stabilisation experiments on ASDEX Upgrade

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## Introduction

Pre-emptive stabilisation of a neoclassical tearing mode, NTM, using the magnetic equilibrium from a real-time Grad-Shafranov solver to feedback control a launching mirror has been demonstrated in ASDEX Upgrade. Real-time magnetic equilibria are calculated by a Grad-Shafranov solver constrained to fit 40 magnetic probes and 18 flux loop differences. A second solver, that includes 10 further constraints from the Motional Stark Effect, MSE, diagnostic, runs simultaneously with a cycle time of 0.60 ms for 6 fitting coefficients. The 33x65 poloidal flux matrix is available on the reflective memory network with a 2 ms cycle time. Pre-emptive NTM stabilisation also has been demonstrated on JT-60U [1] and DIII-D [2]. In ASDEX Upgrade NTM stabilization experiments, correlated temperature and magnetic fluctuations are used to localise a mode that is already present in the discharge [3].

The microwave ray tracing code, TORBEAM [4], requires real-time magnetic equilibria to calculate the mirror angle necessary for electron cyclotron current drive (ECCD) on the rational surface where the NTM is located. The safety factor profile, $q(\psi_N)$, is calculated from the flux surface contour integrals at ten values of normalised poloidal flux, $\psi_N$. Rational surfaces can then be located as a function of normalised radius by spline interpolation. The line integrated phase shift of five chords of a DCN laser interferometer are processed using the flux surfaces to provide an electron density profile by Abel inversion in real-time [5]. The normalised radii of the rational q surfaces, the electron density profile and the poloidal flux matrix are communicated by the reflective memory network to the real-time TORBEAM simulations. The calculation of the mirror angle for ECCD at the required normalised radius includes compensation for microwave beam refraction in the presence of electron density gradients.

## NTM stabilisation experiments

A NTM with m/n = 3/2 was present in a 1 MA discharge with up to 12.5 MW NBI and 1.4 MW ECRH heating. The normalised radius of this mode can be inferred from electron temperature, $T_e$, fluctuation measurements at the mode frequency of the NTM. The phase jump of the fluctuation is related to the change in phase of the $T_e$ fluctuation around the NTM magnetic island [6, 7, 8]. These measurements indicate that the NTM is located at a normalised radius of about 0.6. The basis current profiles for the Grad-Shafranov solver are chosen so that the predicted normalised radius is sufficiently accurate to perform NTM stabilisation experiments.

Shown in Figure 1, is the normalised radius measured by $T_e$ fluctuations at the NTM frequency and the predicted normalised radius of the m/n = 3/2 rational surface by the real-time Grad-Shafranov solver. In this discharge, the mirror angle was scanned to vary ECCD power deposition as a function of the normalised radius. From the magnetic fluctuation amplitude of the m/n = 3/2 mode, the NTM is present after 2.4 s. At 5.1 s a small dip in amplitude, corresponding to partial ECCD stabilisation, is indicated. From this dip it is inferred that the NTM is located at a normalised radius of 0.57, while the $T_e$ fluctuations yield a value of 0.58. From the magnetic equilibrium, a value of 0.60 is predicted. If the current profile were sufficiently well determined by the Grad-Shafranov solver, it would be expected that all three measurements would be in exact agreement. A pre-programmed mirror angle offset is therefore required to perfectly align the ECCD and mode location from the Grad-Shafranov solver. The MSE measurements were not available for use as constraints in the equilibrium reconstruction for these experiments. It is known that these constraints in the plasma centre are needed to accurately determine the internal current density profile and q profile [9].

It also has been observed that the magnetic island may not be symmetric about a flux surface [10]. This implies that the rational flux surface and the optimal point of normalised radius for ECCD deposition in the centre of a large magnetic island may not be aligned. A small offset would then be required for NTM stabilisation using the normalised radius of the rational flux surface calculated by the Grad-Shafranov solver. Additionally, the need for a pre-programmed offset could be related to the uncertainty in the absolute value of the toroidal magnetic field. The evaluation of modulated ECRH power experiments and the measured phase and amplitude response of electron cyclotron emission, ECE, channels shows that the measured deposition radius is accurate to within +/-0.5% of the nominal toroidal field inferred from a highly accurate toroidal field coil current measurement (+/-0.1%). Such a systematic error would lead to changes in the calculated normalised radii of the ECCD deposition and ECE channels.

In Figure 2, the mirror is aimed by feedback control to place ECCD deposition at the normalised radius of the rational surface predicted by the real-time Grad-Shafranov solver plus mirror angle offset. Simulations of feedback control have been carried out to optimise the mirror controller [11]. Comparing the amplitude of the magnetic fluctuations at the NTM frequency in this and the previous discharge, it can be seen that the NTM is stabilised even in the extended period of maximum NBI heating. The NTM cannot be localised by $T_e$ fluctuations as their amplitude has been greatly reduced.

The growth of the NTM during pre-emptive stabilisation in a subsequent discharge was due to a small difference in the evolution of the scenario, with a change in the radial location of the NTM that was not recovered by the real-time equilibrium calculations. The normalised radius of the mode inferred from the $T_e$ fluctuations showed that the mode moved inwards, so that it is possible that the NTM was destabilised by ECCD deposition outside of the the rational q surface. It is concluded that the inclusion of MSE constraints for magnetic equilibrium reconstruction is essential to ensure that pre-emptive NTM stabilisation is suitable for routine operation. Nevertheless, pre-emptive stabilisation has been achieved using the real-time estimated rational flux surface plus an offset.

## Conclusion

Feedback control of a mirror launcher for pre-emptive NTM stabilisation experiments using real-time magnetic equilibria could be demonstrated. A pre-programmed launcher mirror angle offset is required to perfectly align the ECCD and NTM location in these experiments. In a subsequent discharge, the NTM was initially stabilized but then grew during the period of ECCD deposition. This was due to a change in the radial location of the mode that was not able to be recovered by equilibrium constraints using external magnetic measurements only. It is concluded that the availability of MSE constraints for equilibrium reconstruction is essential to determine the spatial location of the rational q surface with sufficient accuracy to make pre-emptive NTM stabilisation a robust tool for improving plasma performance.

## References

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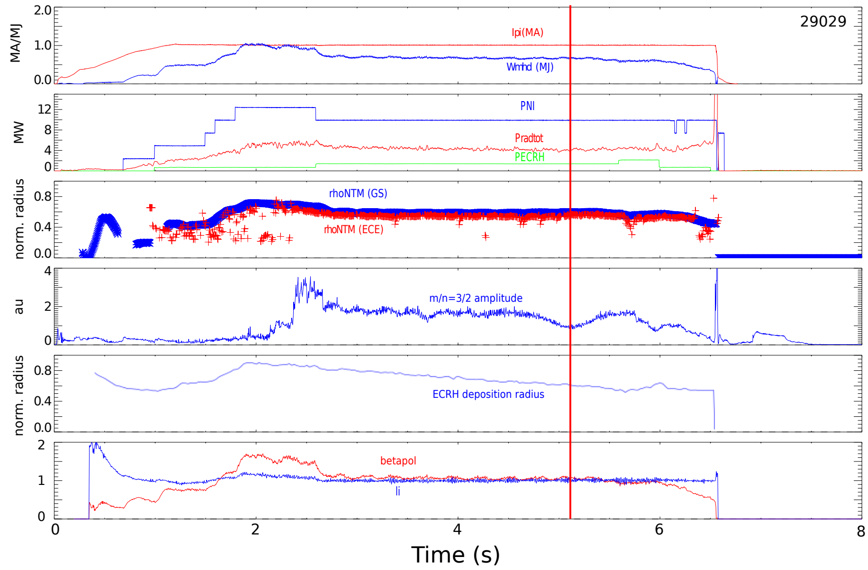


Figure 1: *Time evolution of normalised radius of the 3/2 mode ( rhoNTM(GS) ) predicted from the real-time magnetic equilibrium compared to that measured by ECE temperature fluctuations ( rhoNTM(ECE) ). From the magnetic fluctuation amplitude of the m/n = 3/2 mode, the NTM is present after 2.4 s while at 5.1 s a small dip corresponding to partial ECCD stabilisation is indicated.*

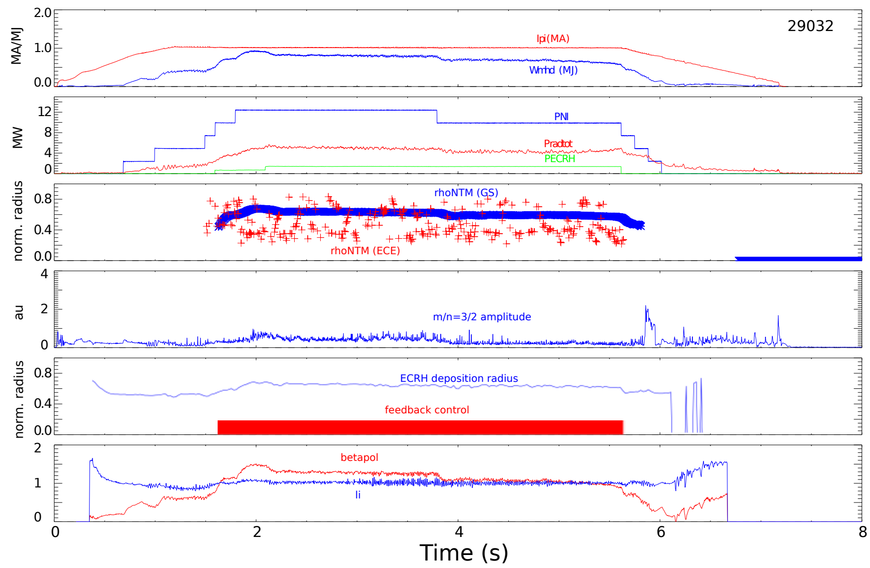


Figure 2: *Pre-emptive stabilisation of the 3/2 NTM mode. The mirror position is feedback controlled from the location of the normalised radius of the NTM calculated from the real-time magnetic equilibrium. Real-time calculations of microwave beam refraction are performed by the microwave ray tracing code, TORBEAM. The NTM cannot be localised as the temperature fluctuation amplitude of the NTM has been greatly reduced. Consequently, the normalised radius of the NTM measured by temperature fluctuations displays a large scatter.*