Neoclassical tearing mode control using vertical shifts on MAST

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Introduction

2/1 NTMs are a concern for future devices as they degrade core confinement [1] and frequently result in locked tearing modes that cause plasma disruptions. Spherical tokamaks are over-dense to conventional electron cyclotron waves and therefore cannot be stabilised by electron cyclotron current drive [1]. An alternative stabilization method, where brief H-L mode transitions are triggered using vertical shifts of the plasma magnetic axis was recently tested on the MAST tokamak. This is possible as H-mode access and the height of the edge pedestal on MAST are sensitive to the position of the magnetic axis [2]. Triggered H-L transitions have been shown to stabilise m/n = 2/1 NTMs and prevent locked mode disruptions for several double null discharges on MAST, extending H-mode duration by 100% for these discharges [3], with no significant decrease in electron temperature (T_e), density (n_e) or ion temperature (T_i) in the plasma core (Fig. 1). The H-mode phase is typically recovered, and the NTM removed, within 20 ms of onset using this method. In this paper, the mechanisms by which triggered H-L transitions stabilise NTMs are explored using MAST data, within a broader aim to determine whether this method can be extended to other scenarios and machines.

Effects of H-L transitions on NTM stability

The modified Rutherford equation (MRE) shows the different contributions to NTM stability as a function of island radial width (W). It can be written as,

$$\frac{t_r}{r_s}\frac{dW}{dt} = \Delta' F(W) + 2\frac{dP_e}{dr}\frac{\mu_0 L_q}{B_{pol}}\left(1.4a_1\sqrt{\varepsilon}F_1(W,W_d) + a_2\frac{(q^2-1)L_q}{qR_o}F_2(W,W_d) + a_3 2m_i\frac{T_e}{eB_\theta}\frac{L_q}{L_p}F_3(W)g(\varepsilon,\nu_i,\omega)\right), \qquad (1)$$

where r_s is the rational surface, P_e electron pressure, and F to F_3 represent functions which describe dependencies on W and finite island width (W_d) (Fig. 2). Each term in equation 1 has been fully described by Snape et al. [4].

The bootstrap drive is represented by $2\frac{dP_e}{dr}\frac{\mu_0 L_q}{B_{pol}}1.4a_1\sqrt{\varepsilon}F_1(W,W_d)$ in the MRE. As an island grows, $\frac{dP_e}{dr}$ is reduced and this creates a hole (ΔI_{BS}) in the bootstrap current, which further drives island growth. The size of this reduction depends on the degree of flattening of the n_e

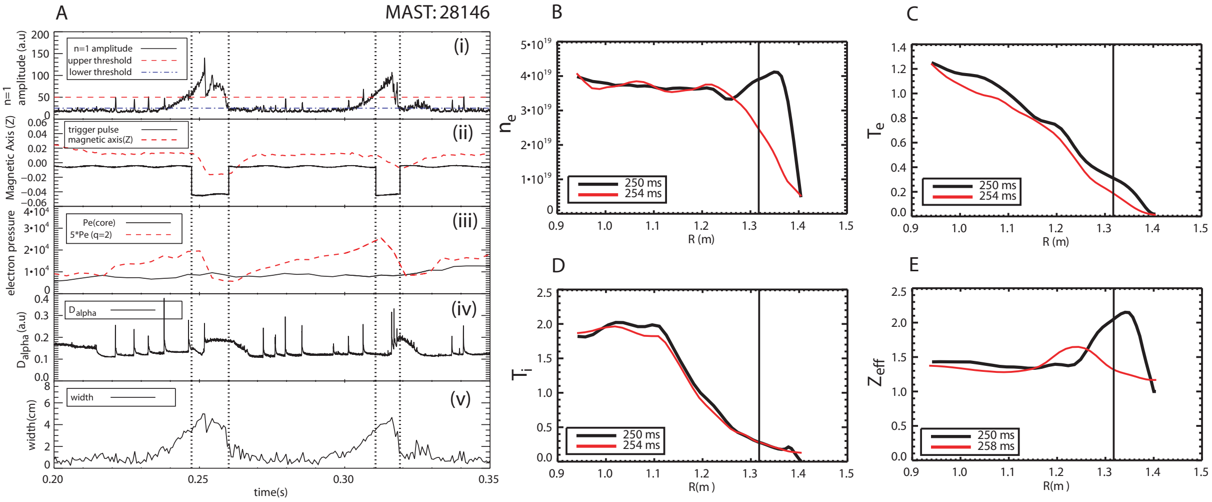

Figure 1: Removal of 2/1 NTM using two triggered vertical shifts. **A (i)**. n=1 amplitude. **ii**. Trigger pulse (red line) and resulting 1.5 cm vertical axis (black line) shift. **iii & iv**. Each shift causes a drop from ELMy H-mode to L-mode; seen as changes in P_e and D_{alpha} respectively. **v**. Evolution of NTM width; the NTM disappears at both 0.265 s and 0.33 s. **B-E** show n_e, T_e, T_i and Z_{eff} respectively before and after H-L transition. The Z_{eff} is determined using carbon density measurements asssuming carbon is the only impurity.

and T_e profiles, which is described by a W_d term for each [5]. Generally W_{d,T_e} « W_{d,n_e} and therefore $\frac{dT_e}{dr}$ shows a much greater reduction than $\frac{dn_e}{dr}$ during island growth and thus the size of the bootstrap hole is predominantly determined by $\frac{dT_e}{dr}n_e$. A triggered H-L mode transition causes a reduction of n_e at the island location and usually no change in $\frac{dT_e}{dr}$. This reduction in n_e reduces the dominant $\frac{dT_e}{dr}n_e$ term and H-L transitions are therefore predicted to decrease the size of a perturbed bootstrap current hole. The bootstrap drive term is, therefore, represented by $2n_e\frac{dT_e}{dr}\frac{\mu_0 L_q}{B_{pol}}1.4a_1\sqrt{\varepsilon}F_1(W,W_d)$ in the MRE when $W_{d,n_e}>W$.

During a triggered H-L shift the $\frac{dP_e}{dr}$ at the $q=2$ rational surface is found to increase and both the tokamak curvature (Δ_{ggj}) and ion polarisation terms (Δ_{pol}) in equation 1 scale with $\frac{dP_e}{dr}$ and $\frac{(\frac{dP_e}{dr})^2}{P_e}$; both terms are stabilising. A triggered vertical shift results in a reduction in the destabilising bootstrap drive (Δ_{bs}) and an increase in the stabilising Δ_{ggj} and Δ_{pol} terms. The magnitudes of these terms, excluding any width dependencies, are shown in Fig. 2A. Their respective dependencies on W are also shown in Fig. 2B. Δ_{ggj} and Δ_{pol} both have a larger influence at smaller W, which indicates that the triggered H-L mode transitions are more effective at smaller W. A large uncertainty exists in the theoretical description of $g(\varepsilon,\nu_i,\omega)$, and therefore the size of Δ_{pol}, and thus measurements of this term are mostly qualitative.

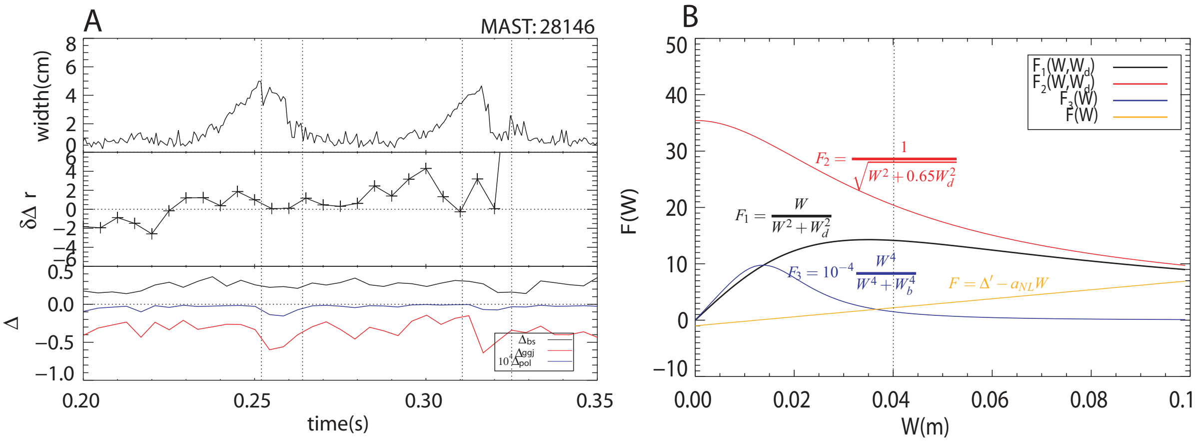

Figure 2: **A** Evolution of NTM width (top plot). Evolution of $\delta\Delta' r$ calculated from MSE data (middle plot). The drive for the different MRE terms excluding the dependencies on W and W_d (bottom plot). **B** The W dependency of each term where $W_d = 0.035$ m. The dotted line at 0.04 m is the W at which triggered H-L transitions occur.

Changes to the classical tearing stability term

EFIT reconstructions and estimates of the current profile using the motional Stark effect (MSE) diagnostic show a hole in the current profile develops inside the H-mode pedestal, near r_s (Fig. 3). This may make Δ' destabilising and it is likely that triggered H-L transitions remove this hole by modifying the bootstrap current and increasing the inductive current density inside the pedestal via reduction in Z_{eff} (Fig. 1). A simple model has been developed in order to examine the effects of the ‘current hole’ on Δ'. This uses an expression, describing Δ' modification by addition of a Gaussian current profile [1], that was adapted by reversing the current drive sign,

$$\delta\Delta' r \approx -\frac{5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{hole}} F(x) \frac{J_{hole}}{J_{\parallel}}, \tag{2}$$

$$F(x) = 1 - 2.43x + 1.40x^2 - 0.23x^3, \tag{3}$$

where the shape parameter (a_2) is taken as 4 (low aspect ratio value), δ_{hole} the full-width half maximum of the Gaussian hole and $x = |r_s - r_{hole}| / \delta_{hole}$; $F(x)$ depends on the alignment of the current hole with r_s. $F(x)$ is destabilising when $x < 0.6$ and stabilising when $0.6 < x < 1$. The model predicts $\delta\Delta' r$ to be stabilising (- $\delta\Delta' r$) when $x < 0.6$ and destabilising (+ $\delta\Delta' r$) as the current profile evolves and r_s moves outwards. Using it with MAST shot 28146, with toroidal current profile (j_ϕ) and safety factor (q) determined directly from MAST MSE [6, 7], a positive $\delta\Delta' r$ is well matched with 2/1 NTM onsets and stabilisation with the first H-L transition (Fig. 2(ii), Fig. 3). However, the model predicts a large positive $\delta\Delta' r$ at a number of points during the second H-L transition when the island is stabilised.

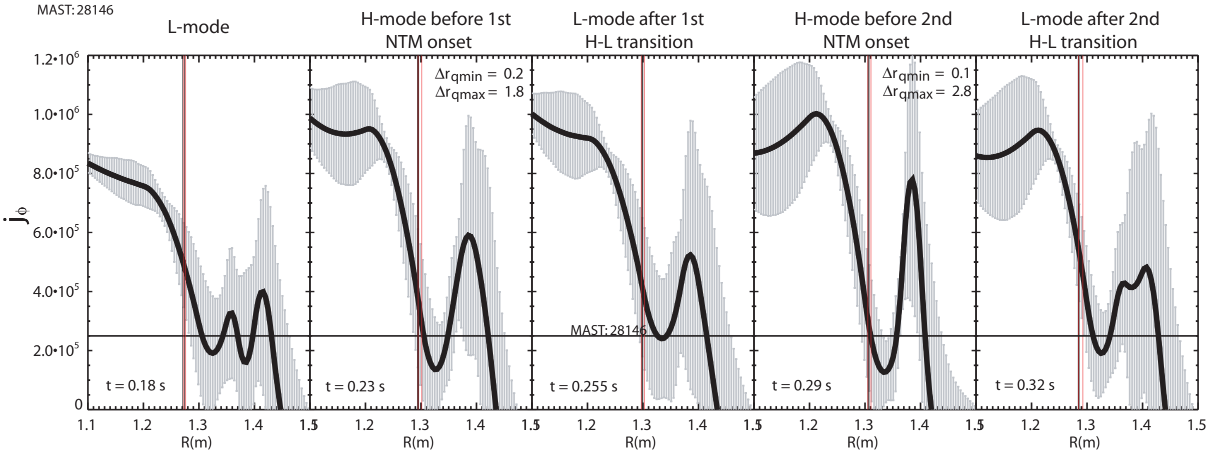

Figure 3: j_ϕ profiles and $q = 2$ positions before NTM onset and after H-L transition. The baseline j_ϕ (2.5e5 kA/m) is taken at the first L-mode profile (t=0.18 s). Current holes are modelled as perturbations from this value.

Conclusion and future work

Triggered H-L mode transitions stabilise 2/1 NTMs on a number of MAST discharges and the mechanism is likely to be via a reduction in the destabilising terms Δ_{bs} and Δ', in addition to an increase in the stabilising Δ_{ggj} term. Here it is proposed that ‘current holes’ are responsible for positive Δ' and triggerless tearing modes in the shots examined. However, more discharge data is needed to further test and refine this model. Further work will also focus on testing this scheme in different scenarios, in particular those with greater bootstrap drive, and on improvements to triggering hardware in order to permit triggering of H-L transitions at smaller island widths where they are expected to be more efficient. This work was funded by the UK Engineering and Physical Sciences Research Council under grants EP/I501045 and EP/H049460/1.

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