Letter

Neoclassical tearing mode control using vertical shifts on MAST

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Abstract

Triggered vertical shifts of the MAST spherical tokamak plasma have been found to stabilize 2/1 neoclassical tearing modes (NTMs) for a number of MAST shots, without impacting on core confinement. This stabilization is a result of favourable modifications of the density, temperature and pressure profiles at the location of an NTM by means of a brief transition from high (H) to low (L) confinement mode. Using this method, the high confinement phase can typically be recovered, and the NTM removed, within 20 ms of onset.

Keywords: tearing modes, tokamaks, spherical tokamaks, magnetic islands, macro instabilities

(Some figures may appear in colour only in the online journal)

1. Introduction

A major performance limitation for future magnetically confined fusion (MCF) devices is predicted to be the onset of neoclassical tearing modes (NTMs) [1–4], which can give rise to a soft beta limit. If NTMs grow to a saturated size they can cause plasma terminating disruptions and unacceptable damage to the first wall of the device. Spherical tokamaks (STs) are being investigated as more compact potential MCF devices and have a number of advantages over the conventional tokamak scheme [5]. However, STs are over-dense to conventional electron cyclotron waves and therefore cannot use the electron cyclotron current drive (ECCD) that is conventionally used to stabilize NTMs [6–8]. An alternative stabilization method has recently been demonstrated on MAST and is reported here. It involves brief transitions from high (H) to low (L) confinement modes, which are triggered using controlled vertical shifts of the plasma magnetic axis. Such transitions are possible because on MAST both H-mode access and edge pedestal height are sensitive to the position of the magnetic axis [9].

Triggered H–L transitions are shown to stabilize \(m/n = 2/1\) NTMs (where \(m\) is the poloidal mode number and \(n\) the toroidal mode number) and prevent locked mode disruptions for several double null discharges on MAST, typically doubling the H-mode duration [10], with no significant lasting decrease in electron temperature \((T_e)\), density \((n_e)\) or ion temperature \((T_i)\) measured in the plasma core (figure 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 stabilize 2/1 NTMs are explored using MAST data.

2. Description of Experiments performed

The MAST discharges reported here are double null, 800 kA plasma current \((I_p)\) discharges each with a toroidal field \((B_T)\) of 0.5 T at the magnetic axis and beam heating of 2–4 MW. This scenario is characterized by weakly reversed shear \(q\) profiles and high performance, typically reaching \(\rho_n \geq 3\). Here, \(q\) is the safety factor, which represents the number times a magnetic field line travels around a torus toroidally (\(n\)) for each time around poloidally (\(m\)) and \(\rho_n\) is the ratio of \(\beta_T\) \((\beta_T = \langle P \rangle/(B_T^2/2\mu_0))\) to the Troyon limit \((I_p/a B_T)\), where \(\langle P \rangle\) is the volume averaged total pressure, \(B_T^2/2\mu_0\) is the magnetic energy density and \(a\) is the minor radius [12].

The shots typically transition into H-mode at \(\sim 0.2\) s and a 2/1 NTM occurs a short time (20–50 ms) later. Although 2/1 NTMs occur frequently in other high performance scenarios on MAST and also result in locked mode disruptions, this particular scenario was chosen because its performance ensures the early appearance of a 2/1 NTM. A field
temperature and pressure are maintained (figures 1, 2 and 3). Enhanced core confinement is found to be largely unaffected and fast ion pressure (steep gradient region that results from reduced ion transport in the current flat top phase, the position for H-mode access and H-mode is rapidly restored. NTM. At this point, the vertical position returns to the optimum of 1–2 cm in these scenarios result in an H–L back transition on MAST. Vertical shifts of the order of magnitude. In order to accurately describe the pressure and current in this region, the equilibrium boundary is first determined using EFIT code. The fixed boundary code CHEASE [14] is then used to recalculate the equilibrium using high resolution measurements of pressure, current and poloidal flux from the MAST motional Stark effect (MSE) magnetic field internal pitch angle profile diagnostic, using a method previously described by Petty et al [15] and DeBock et al [16].

The $f^f$ and $P^f$ terms required for the equilibrium solution are calculated directly from MSE data, where $f^f$ is the product of the poloidal current flux function ($f$) and its derivative with respect to poloidal flux ($f'$) and $P^f$ is the derivative of the plasma pressure with respect to the poloidal flux. The $P^f$ term at $q = 2$ agrees well with the total pressure profile estimated from Thomson scattering (TS) and charge exchange (CXR) data (figure 3). The fast ion contribution, which was not directly measured on these discharges, agrees qualitatively with estimates from transport codes. The bootstrap current terms are then calculated using TS, CXR and visible bremsstrahlung (ZEBRA) profile measurements of the $T_e$, $n_e$, $T_i$ and $Z_{eff}$ profiles, where $Z_{eff}$ is the effective charge of the plasma as defined in Wesson et al [12].

3. Effects of H–L transitions on NTM stability

The modified Rutherford equation (MRE) details the different contributions to NTM stability as a function of island full radial width ($W$). It can be written as the sum of the classical stability term ($\Delta'_CL$), the bootstrap drive term ($\Delta'_BS$), the magnetic field curvature term ($\Delta'_GGJ$) and the ion polarization term ($\Delta'_POL$). These terms can be calculated using equilibrium codes and written in terms of measurable parameters, and the form used here is very similar to that used in previous works [11, 18–20].

$$\frac{dW}{dr} = \Delta'_CL + \Delta'_BS + \Delta'_GGJ + \Delta'_POL$$

(1)

$$\Delta'_CL = \Delta' - \alpha_{QL} W + \delta A'$$

(2)

$$\Delta'_BS,\beta_p = 1.4\sqrt{\epsilon_1 \beta_p} \frac{L_q}{\epsilon_2} \frac{W}{W^2 + W_d^2}$$

(3)

$$\Delta'_BS,\beta_p = 1.04\sqrt{\epsilon_1 \beta_p} \frac{L_q}{\epsilon_2} \frac{W}{W^2 + W_d^2}$$

(4)

$$\Delta'_POL = -\alpha_3 D_T \frac{1}{W^2 + 0.65W_{d,T}}$$

(5)

Here, $r_s$ is the minor radius of the rational surface, $t_i$ the resistive time, $P_e$ the electron pressure, $P$ the total pressure, $W_d$ the finite island transport diffusion width, $W_d,T$ the finite island heat transport diffusion width, $W_{b_i}$ the ion banana width, $D_T$ the resistive interchange term, ($B_0$) the flux average poloidal magnetic field, $L_q$ the safety factor gradient scale length ($L_q = q(dq/dr)^{-1}$), $L_p$ the pressure gradient scale length ($L_p = p(dp/dr)^{-1}$) and $P_{pol}$ is the ratio of kinetic pressure to poloidal magnetic pressure ($P_{pol} = 2\mu_0 P/(B_0)^2$). In equation (1), the ion profile contribution to the bootstrap term has been neglected because of a high trapped fraction ($\sim 80\%$) at the location of the $q = 2$ rational surface.
Figure 2. Changes induced in the geometry and kinetic profiles before (black lines) and after (red lines) the triggered H–L transitions in MAST shot 28146. (a). A cross section of the MAST vessel showing the changes in the geometry of the last closed flux surface (LCFS) and at the location of the 2/1 NTM surface. (b). The carbon, ion and electron densities. (c). The electron and ion temperatures. The vertical lines in (b) and (c) show the radial location of the 2/1 NTM.

Figure 3. (a). The total kinetic pressure ($P_T$) and the pressure derived from MSE ($P_{MSE}$), which includes the fast ion pressure. (b). The flux average current density and the bootstrap current density determined using the Sauter formula [17].

The standard forms of $\Delta_{BS}^{'} \beta_p$ and $\Delta_{POL}^{'} \beta_p$ are shown in equations (3) and (5) respectively. These expressions are typically used in experiments where $\beta_p$ scans are performed [11, 18, 20, 21] and assume a constant $L_p$ during the island evolution. As transient H–L–H transitions principally modify $L_p$, these stability terms has been rewritten in terms of the $P$ and $dP/dr$, by substituting $L_p$ and $\beta_p$ into equations (3) and (5). $W_{d,T_e}$ and the coefficients $a_{NL}$, $a_1$, $a_2$ and $a_3$ are kept fixed during the time evolution of the mode and have been determined from fitting a heat transport model and previous beta scan experiments respectively on similar MAST discharges [11]. The values used for these coefficients are shown in table 1 and, as discussed by Snape et al [11], are close to the theoretically expected sizes.

| Parameter | $\Delta_{BS}$ | $a_1$ | $a_2$ | $a_3$ | $W_{d,T_e}$ |
|-----------|----------------|-------|-------|-------|--------------|
| Values    | $-1$           | $30$  | $-3.3$| $7.7$ | $1.4$        |
|           |                |       |       |       | $1.8$ (cm)   |
|           |                |       |       |       | $3.5$ (cm)   |

In conventional aspect ratio tokamaks ECCD is the favoured scheme for NTM control and mitigation. ECCD modifies NTM stability by the addition of a localized current at the position of the NTM, which makes $\Delta_{Cl}$ more stabilizing.
and replaces the missing bootstrap current. However, transient H–L–H mode transitions are found to influence both the pressure and current at the NTM location and, as a result, modify all stability terms in equation (1). The effects of these transitions on each on the stability terms will now be considered in turn.

3.1. Changes to the resistivity

An H–L transition reduces \( T_i \) and \( Z_{\text{eff}} \) (figure 3) and results in an increase in plasma resistivity (\( \eta \)) at the \( q = 2 \) surface. The size of the resistive time (\( t_r = 1.22 \mu s T_i^2 / \eta \)) determines the timescale over which the current profile can evolve on a given length scale (\( l \)). The value of \( t_r \) is important in determining how quickly \( W \) can change (equation (1)). \( t_r \) is reduced during an H–L transition and as \( dW/dt \) is proportional to \( 1/t_r \), this in turn increases the magnitude of \( dW/dt \). As an H–L transition is stabilizing (\( dW/dt \) is negative) this enhances NTM stability (figure 3(b)). If the length scale of interest is assumed to be \( \sim 15 \text{ cm} \), the \( t_r \) in these discharges (1 < \( t_r \) < 5 ms) matches the typical time scale of island decay.

3.2. Changes to the bootstrap stability term

The bootstrap drive is typically regarded as the principal destabilizing term which drives NTMs and is represented by \( 1.4 \sqrt{e} a_1 L_q \frac{dn_e}{dr} (R_0) \frac{W}{qR_0} \) in the MRE. This effect of the bootstrap current on tearing mode stability was first predicted by Rutherford et al [22] and NTMs were first identified experimentally in TFTR [1]. Experimental measurements showed there to be a threshold island width above which NTMs grow and the two principal mechanisms proposed to explain this threshold are the effects of the finite island width and the ion polarization current. The effect of the ion polarization current is discussed further in the next section.

As an NTM grows, \( \frac{dr}{dt} \) is locally reduced at the island position and this creates a hole in the bootstrap current, which then further drives NTM growth. The size of this reduction depends on the degree of flattening of the \( n_e \) and \( T_e \) profiles, which is described by the finite island width (\( W_{\text{d,T}} \)) for each [23]. The finite island width used in this paper is \( W_{\text{d,T}} \) and has been determined from fitting a heat transport model from Fitzpatrick et al [23] to TS electron temperature profiles of similar discharges as discussed in Snape et al [11].

Generally \( W_{\text{d,T}} \ll W_{\text{d,n}} \), and therefore \( \frac{dr}{dt} \) shows a much greater reduction than \( \frac{dn_e}{dt} \) during NTM growth. Thus, the size of the bootstrap hole is predominantly determined by \( \frac{dr}{dt} \). A triggered H–L transition causes a reduction of \( n_e \) at the island location, but usually little change in \( \frac{dr}{dt} \). The reduction in \( n_e \) reduces the dominant \( \frac{dr}{dt} n_e \) 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 \( 1.4 \sqrt{e} a_1 L_q \frac{dn_e}{dr} (R_0) \frac{W}{qR_0} \) in the MRE when \( W_{\text{d,n}} > W \). The different contributions of these terms to the overall bootstrap drive are shown in figure 4(c).

3.3. Changes to the curvature and polarization current stability term

\( \Delta_{\text{GGJ}} \) is the stabilizing contribution of the magnetic field curvature and is typically an order of magnitude larger in STs than in conventional aspect ratio tokamaks, as a result of the high level of plasma shaping in these machines. Glasser, Greene and Johnson derived the mathematics to describe this stabilizing contribution [24], which is referred to as the Glasser Green Johnson (GGJ) effect. The dependence of the \( \Delta_{\text{GGJ}} \) term on \( W \) was modified by Lutjens et al [25] to take into account the finite island width. The size of \( \Delta_{\text{GGJ}} \) is dependent on the resistive interchange parameter \( D_r \) calculated from the CHEASE code. \( D_r \) is proportional to \( \frac{dr}{dt} \) and this can be seen in its low aspect ratio approximation [11], given by \( q_i (\eta - 1) \frac{dr}{dt} \frac{1}{\rho R_0} \).

The size of the ion polarization term [26, 27] is dependent on how ions and electrons respond to the island rotation (\( \omega \)) in the rest frame of the plasma, given by the difference in island frequency measured in the lab frame (\( \omega_M \)) and the frequency where the electric field is zero (\( \omega_{E=0} \)) [28]. This complex dependency is represented by \( g(\epsilon, \nu, \omega) \) in equation (5), where \( \nu \) is the ion collisional frequency. During vertical shifts the \( \omega_M \) is reduced by a factor of two in 100 \( \mu s \), a similar decrease is found in the \( \omega_{E=0} \). However, the minimum time resolution of this measurement is 500 \( \mu s \). The value of \( \Delta_{\text{POL}} \) plotted in figure 4(d) therefore assumes that \( g(\epsilon, \nu, \omega) \) does not vary as a result of the H–L transition. A large uncertainty exists in the theoretical description of \( g(\epsilon, \nu, \omega) \) and in the absence of a complete theory, the unknown contribution is absorbed into the dimensionless fitting parameter \( a_1 \) and therefore the size of \( \Delta_{\text{POL}} \), and thus measurements of this term, are mostly qualitative. In order to limit the effect of the ion polarization term below the ion banana width we have adopted the heuristic model of Sauter et al [29].
During a triggered H–L shift the \( \frac{d^2 r}{dr^2} \) at the \( q = 2 \) rational surface is found to increase and the tokamak curvature (\( \Delta_{GGJ} \)) and ion polarization (\( \Delta_{POL} \)) terms, in equations (4) and (5) respectively, scale with \( \frac{d^2 r}{dr^2} \) and \( \frac{d^2 \delta}{dL^2} \). A triggered vertical shift results in a reduction in the destabilizing bootstrap drive (\( \Delta_{bs} \)) and an increase in the stabilizing \( \Delta_{GGJ} \) and \( \Delta_{POL} \) terms; the magnitudes of these terms are shown in figure 4(d). \( \Delta_{GGJ} \) and \( \Delta_{POL} \) both have larger influences at smaller \( W \), which indicates that the triggered H–L mode transitions are more effective at smaller \( W \). The size of the \( \Delta_{GGJ} \) term may have different dependencies on \( T_e, T_i \) and \( n_s \) profiles similar to the \( \Delta_{bs} \), but no complete theory exists to describe these dependencies.

3.4. Changes to the classical tearing stability term

The classical tearing stability term [30, 31] is generally assumed to be stabilizing, as if it were not, tearing modes would be present in all discharges. However, a growing body of work [11, 32] suggests that this term can be modified to be weakly stabilizing or destabilizing, depending on the evolution of plasma parameters. In the discharges used in this work, the onset of the NTM occurs without a clear trigger, which suggests that \( \Delta_{CS} \) evolves towards a point of being weakly stabilizing or destabilizing. EFIT reconstructions and estimates of the current profile using the MSE diagnostic show a hole develops in the current profile (\( \langle J_{hole} \rangle \)) inside the H-mode pedestal, near \( r_s \) (figure 3). This may make \( \Delta_{CS} \) destabilizing and it is likely that triggered H–L transitions remove this hole, by modifying the bootstrap current (\( \langle J_{bs} \rangle \)) and increasing the inductive current density inside the pedestal via a reduction in \( Z_{eff} \) (figure 1). A full calculation of \( \Delta_{CL} \) in a realistic tokamak geometry remains a challenging problem. Here, a simple model has been developed in order to qualitatively estimate the effects of the ‘current hole’ on \( \Delta_{CL} \) and uses an expression describing the modification of \( \Delta_{CL} \) by the addition of a Gaussian current profile. This expression was previously developed to incorporate the ECCD current drive into the MRE framework [8, 33] and here is simply adapted by reversing the current drive sign to represent a current hole, 

\[
\delta \Delta' \approx - \frac{5 \pi^{3/2}}{32r_s} \frac{L_a}{\delta_{hole}} F(x) \frac{\langle J_{hole} \rangle}{\langle J \rangle},
\]

\[
\delta \Delta_{bs} \approx - \frac{5 \pi^{3/2}}{32r_s} \frac{L_a}{\delta_{hole}} F(x) \frac{\langle J_{bs} \rangle}{\langle J \rangle},
\]

\[
F(x) = 1 - 2.43x + 1.40x^2 - 0.23x^3,
\]

where the shape parameter (\( a_s \)) is taken as 4 (low aspect ratio value), \( \delta_{hole} \) is the full-width half maximum of the Gaussian hole and \( x = \frac{r_{s} - r_{hole}}{r_{s}} \). \( F(x) \) depends on the alignment of the current hole with \( r_{s} \). \( F(x) \) is destabilizing when \( x < 0.6 \) and stabilizing when \( 0.6 < x < 1 \).

\( \delta \Delta_{bs} \) is determined from the hole in the derived (\( J_{bs} \)) profile and \( \delta \Delta' \) from the estimated (\( J \)) profile. Typically, as the \( q \) profile evolves, then \( r_{s} \) becomes more closely aligned with the current hole and this term is more destabilizing. The evolution of these terms is shown in figure 4(b). In the case of the \( \delta \Delta_{bs} \) the current hole is predicted to be initially stabilizing, but to become destabilizing as the shot evolves, whilst \( \delta \Delta' \) is found to be destabilizing for the entire shot. In both cases, the triggered H–L transition is found to remove, or significantly reduce, the current hole and both \( \delta \Delta_{bs} \) and \( \delta \Delta' \) are reduced to approximately zero.

4. Merits of this NTM stabilization scheme

This approach has a number of advantages which may permit further application on ST. The most unstable tearing modes are expected in the high edge magnetic shear which is typical in close proximity to the pedestal region, coupling the evolution of the H-mode pedestal profiles to those at the location of the mode. Evidence of this coupling has also been observed on the conventional aspect ratio tokamak DIII-D [34]. The drop in density associated with an H–L transition reduces the bootstrap drive term. The increase in the overall pressure gradient drives the stabilizing tokamak curvature and ion polarization terms. On STs, the curvature term is large enough to rival the bootstrap drive and an order of magnitude greater than on conventional tokamaks [11, 35].

The theory of the ion polarization term remains incomplete, but comparisons with current theories are encouraging. Current hole formation as a result of pedestal bootstrap current and impurity accumulation are suggested as a means of reducing \( \Delta_{CL} \). Brief H–L transitions can modify (\( J_{s} \)), removing current holes centred on the \( r_{s} \).

Brief H–L transitions are found to have little effect on the core temperature, density and pressure obtained in MAST. This may be a result of the core performance on MAST being dominated by suppression of the ion temperature gradient (ITG) turbulence [36] rather than by the edge pedestal performance. In a number of other tokamaks a linear scaling has been obtained between the edge pressure and the core confinement and therefore more work is needed to characterize the effect of brief transitions on other devices.

On MAST, the sensitivity of H-mode access on the vertical positions is used to trigger H–L transitions when the signature of 2/1 NTMs is detected by the magnetic coils. This mechanism is sufficient to trigger an H–L transition at maximum input power on MAST. A range of methods exist to trigger similar transitions on existing conventional and spherical tokamaks, as discussed by Meyer et al [9]. One of the possible disadvantages of this scheme is a high divertor heat flux (8 MW m\(^{-2}\)) associated with the H–L transition, which is of the order of a typical type I edge localized mode (ELM) [12] on MAST. ELMs are instabilities which occur in H-mode plasmas and cause heat loads on the tokamak’s divertor. A number of new divertors designed [37, 38] to handle high ELM heat fluxes are currently being built [39] and tested and it is anticipated that successful operation of these schemes will mitigate this problem.

5. Conclusion and future work

Triggered, transient H–L–H mode transitions, induced by small vertical plasma displacements, have been demonstrated
as a method for removing 2/1 NTMs in high performance discharges on MAST, extending the H-mode duration by a factor of two. A detailed analysis of changes to the terms in the MRE suggests that the stabilization mechanism is likely to be via a reduction in the destabilizing terms $\Delta_{\text{gs}}$ and $\Delta_{\text{cl}}$, as well as an increase in the stabilizing $\Delta_{\text{GGI}}$ and $\Delta_{\text{POL}}$ terms. The modification of these terms is a result of the favourable modification of the kinetic and current profiles during the brief $\text{H} \rightarrow \text{L}$ transitions. Further work will focus on optimizing this scheme on a range of high performance ST scenarios, in particular those with greater bootstrap drives. It will also look to improve the triggering hardware, in order to permit triggering of $\text{H} \rightarrow \text{L}$ transitions at smaller island widths, where this methodology is expected to be more efficient.

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