Impact of resonant magnetic perturbations on the L-H transition on MAST

R Scannell¹, A Kirk¹, M Carr¹, J Hawke², S S Henderson³, T O’Gorman¹, A Patel¹, A Shaw¹, A Thornton¹ and the MAST Team

¹ CCFE, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK
² FOM Institute DIFFER, Dutch Institute for Fundamental Energy Research, Association EURATOM-FOM, 3430 BE Nieuwegein, Netherlands
³ Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, Scotland

E-mail: rory.scannell@ccfe.ac.uk

Received 12 December 2014, revised 14 May 2015
Accepted for publication 20 May 2015
Published 18 June 2015

Abstract
The impact of resonant magnetic perturbations (RMPs) on the power required to access H-mode is examined experimentally on MAST. Applying RMP in \( n = 2, 3, 4 \) and 6 configurations delays the L-H transition at low applied fields and prevents the transition at high fields. The experiment was primarily performed at RMP fields sufficient to cause moderate increases in ELM frequency, \( \frac{f_{\text{mitigated}}}{f_{\text{natural}}} \approx 3 \). To obtain H-mode with RMPs at this field, an increase of injected beam power is required of at least 50% for \( n = 3 \) and \( n = 4 \) RMP and 100% for \( n = 6 \) RMP. In terms of power threshold, this corresponds to increases of at least 20% for \( n = 3 \) and \( n = 4 \) RMPs and 60% for \( n = 6 \) RMPs. This ‘RMP affected’ power threshold is found to increase with RMP magnitude above a certain minimum perturbed field, below which there is no impact on the power threshold. Extrapolations from these results indicate large increases in the L-H power threshold may be required for discharges requiring large mitigated ELM frequency.

Keywords: L-H power threshold, RMP, ELM frequency, resonant magnetic perturbations, L-H threshold, mitigated ELM frequency

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

1. Introduction

The power loading to the divertor during type I ELMs is a concern for large fusion machines [1]. One proposed method to reduce this power loading is the application of resonant magnetic perturbations (RMPs). These RMPs have been used to suppress type I ELMs as demonstrated on DIII-D [2], ASDEX Upgrade [3] and KSTAR [4], however, not all devices with RMPs have achieved suppression. A second possibility is mitigation, which reduces the power loading due to the ELMs, typically by increasing ELM frequency and hence reducing the energy loss per ELM event. Mitigation is observed on a number of tokamaks, notably MAST [5] and JET [6, 7]. A further possible reason for RMPs in future devices is that ELMs may be required at a certain minimum frequency to prevent Tungsten accumulation [8] by increasing particle transport at the edge.

One observed side effect of the application of RMPs is that it makes H-mode access more difficult increasing the L-H Power threshold (\( P_{\text{th}} \)) and hence the requirement for external heating power in order to access H-mode. This increased power requirement is small in absolute terms on current devices. With no applied RMP, the power threshold scales approximately as \( P_{\text{th}} = 0.0488n_{e20}^{0.717}S^{0.94}B_T^{0.8} \) [9], where \( n_{e20} \) is the line average density in \( 10^{20} \text{m}^{-3} \), \( B_T \) is the magnetic field and \( S \) the plasma surface area. This scaling is for experimental conditions close to expected ITER parameters and based on results from standard aspect ratio machines. Extrapolating using this scaling, the power threshold for ITER is predicted to be \( \approx 52 \text{ MW} \) [10]. Increases in the ITER power threshold in the presence of RMP similar to those observed on current devices could potentially be quite large. One positive development is that recent results with the full metal wall on ASDEX Upgrade [11] and JET [12] have indicated that the
power threshold requirement may be reduced by 25–30% with respect to operation with the Carbon wall. However, the L-H power threshold on ITER in the presence of RMP remains a concern particularly due to the uncertainty in the parameters which influence the magnitude of this increased $P_{th}$.

On DIII-D [13] it has been observed that in Deuterium discharges the $P_{th}$ increases once the magnitude of the RMP goes above a critical threshold. Increases in power threshold of up to 100% have been observed at large field perturbation $\delta B/B_T$. Experiments on the impact of RMPs on $P_{th}$ on ASDEX upgrade in $n = 2$ [14] and [9] have been performed showing a 20% increase in $P_{th}$ for $0.45 \ n_{GW} < n_e < 0.65 \ n_{GW}$. In these discharges, the transition during RMP is observed to occur at a higher, less negative, radial electric field minimum. On NSTX [15] an increase in $P_{th}$ of at least 50% is observed on application of RMP. The NSTX results again points to a possible dependence of the increase in $P_{th}$ on changes in the radial electric field magnitude.

On MAST [16], application of $n = 3$ RMP to a 900kA double null discharge results in an increase of required beam power from 1.8 to 3.3 MW to achieve a H-mode transition at the same time as a no applied RMP discharge. In discharges prevented from accessing H-mode by application of RMP, a more positive Lorentz ($v \times B$) component of the radial electric field, as measured from Doppler spectrometry from Helium, is observed. The study that will be presented in this paper differs from [16] in that the resulting plasmas exhibit useful ELM mitigation as a result of the applied RMPs. In addition, the discharges examined in this paper are lower single null discharges as opposed to connected double null, and hence more similar to the ITER shape.

The MAST ELM control system has two rows of coils, 6 in the upper row above the midplane and 12 in the lower row below the midplane. In the lower single null (LSND) configuration the plasma is far from the upper row of RMP coils and hence the perturbation is predominantly from the lower row of 12 coils. These coils allow application of RMPs in $n = 2$, 3, 4 and 6 configurations. Currents of up to 1.4 kA are applied to the RMP coils, to translate these currents to machine independent parameters we also express them in $b_{res}^r$ and $\Delta \sigma_{\text{Chirikov}} > 1$. The parameter $b_{res}^r$ is the maximum resonant component of the applied radial field normalised to the toroidal field, a full definition may be obtained from page 2 of [17] where it is referred to as $b_{res}^r$. For the discharges examined in this paper coil currents of 1.4 kA result in values of $b_{res}^r$ of order $1 \times 10^{-3}$, as shown in section 5. The Chirikov parameter ($\sigma_{\text{Chirikov}}$) is a measure of the island overlap and assuming that the RMPs have a single toroidal component $n$, this parameter is defined as $\sigma_{\text{Chirikov}} = (\delta_m + \delta_{\max})/\Delta_{m, m+1}$ where $\delta_m$ is the half width of the magnetic islands on the on the $q = m/n$ surface (m being the poloidal mode number and $q$ the safety factor) and $\Delta_{m, m+1}$ is the distance between the two surfaces. The region of poloidal flux for which the Chirikov parameter is greater than 1 ($\Delta \sigma_{\text{Chirikov}} > 1$) is used to define the stochastic layer.

For a more general overview of the results of application of RMPs to MAST discharges, the reader is referred to [18] and the references therein. An investigation into the H-mode power threshold scaling with plasma parameters for a number of machines is described in [19]. The power threshold on MAST has been previously investigated in [20], specifically the variation of the power threshold with separatrix configuration [21] and divertor leg length [22].

The impact of RMP on a 600kA discharge with constant fuelling. Section 3 discusses the natural L-H power threshold for 400kA discharges which are the focus for the remainder of this paper. Section 4 looks at the results of an RMP field scan on L-H transition and examines the plasma profiles before the transition. Finally, in section 5, the impact of different toroidal mode number ‘$n$’ RMP configurations on the L-H power threshold are compared and quantified.

2. Impact of RMP on L-H transition at constant fuelling (600kA $n = 6$)

In this section the impact of an applied $n = 6$ RMP field on the L-H transition of a lower single null discharge with a plasma current ($I_p$) of 600kA is examined. The discharges had constant gas fuelling rate, a toroidal field on axis of 0.55T and a $q_{95}$ of 3.5 at 330 ms. To determine the power threshold for similar discharges without RMP a dedicated scan in NBI power was performed. This scan showed that 0.6 MW or greater of applied neutral beam power causes a transition to H-mode. The duration of the plasma current flat top decreases with decreasing neutral beam power and in shots with 0.4 MW or less of injected power the plasma current begins to fall off before the L-H transition time. Hence the L-H power threshold is at most 0.6 MW, but could be lower. This scan was performed at a single line integral density and the variation of the L-H power threshold with density for these lower single null discharges has not been examined. The discharge examined here, to which $n = 6$ RMP was applied, had 1.5 MW of injected neutral beam power and so is well above the L-H power threshold.

The midplane $D_\alpha$ measurements for the no applied RMP and discharges with 1.0 and 1.4 kA in the RMP coils are shown in figures 1(a)–(c). The small spikes in the $D_\alpha$ measurements during the L-mode are indicative of sawteeth which are a feature of these discharges. The L-H transitions in all three discharges show are induced by sawteeth and hence co-incident with the sawtooth event. With no applied RMP the L-H transition occurs at 330 ms. Application of RMP with 1.0kA of current in the coils delays the transition to 375 ms (the subsequent spike in density at 400ms is due to injection of a pellet). Application of RMP with 1.4kA of current in the coils completely suppresses the transition during the plasma current flat top. A subsequent L-H transition in this discharge occurs at 420 ms, however, this transition is induced by the plasma current ramp down and hence not considered to be a ‘natural’ transition. The timing of the $I_p$ ramp down causes the gas to turn off, hence is at the same time as the reduction in gas flow rate as shown in figure 1(d).

In these discharges the gas flow rate was kept constant from 250ms. Upon applying RMP there is a particle pump
out. However, the L-H transition occurs at similar measured line integral density for all three discharges. The result in figure 1 for constant gas flow rate illustrates that the suppression and delay of the L-H transition is due to application of RMP field and not due to change of edge conditions as a result of changing fuelling. In all other discharges discussed in this paper the line integral density is fixed by feedback control on the gas flow in order that the impact on the L-H transition may be observed at constant density. In these discharges with feedback control the RMP field causes a density loss that scales with RMP intensity and hence the gas flow rate increases with increasing RMP field.

The final trace shown in figure 1(f) is the neutron rate as measured by a $^{235}\text{U}$ fission chamber [23] which is similar for all 3 discharges. The neutron rate in these discharges are predominantly due to interaction of injected neutral beam Deuterium with fast ions in the plasma, hence a variation in fast ion loss rate would be expected to change this neutron rate. Since the neutron rates are similar for the discharges shown here, in this case there is no evidence that the RMPs impact on the fast ion confinement as has been observed in certain discharges on other machines [24].

### 3. Power threshold for 400 kA discharges

The impact of RMPs on ELM frequency in MAST plasmas has been widely studied in lower single null discharges with plasma currents of both 600 and 400 kA. Lower single null discharges are chosen as this is the operating configuration for ITER. In the following sections RMP are applied to shots in 400 kA discharges. These 400 kA shots were chosen over the 600 kA discharge for this study because: 1) the 400 kA discharges have fewer sawteeth, hence the triggering of the L-H transition by sawtooth events is less likely 2) the natural ELM frequency and increase in ELM frequency due to application of RMP is easier to observe without the sawtooth induced ELMs triggered in 600 kA discharges and 3) a longer plasma current flat-top duration can be maintained in 400 kA discharges hence allowing longer time for a delayed L-H transition to occur. The 400 kA discharges have a $B_T$ on axis of 0.585 T and a $q_{95}$ of 4.8 at 350 ms, only the period of the plasma current flat top is examined.

The results of a scan in neutral beam power to determine the power threshold in these 400 kA discharges without RMPs is shown in figure 2. The shots are similar with beam power applied from 130 ms (except for beam breakdown in the 1.5 MW discharge which marginally delayed the start time) and the discharges go into density feedback from 310 ms such that the L-H transition in all discharges occurs at the same density. The reduction of beam power from 1.5 to 1.2 MW and then to 0.9 MW does not affect the time of the L-H transition. At 0.6 MW of injected power a delayed transition occurs, followed by a back transition to L-mode and a subsequent L-H transition. This scan indicates the L-H power threshold for no applied RMP in 400 kA discharges corresponds to an injected beam power of 0.6 MW or less.

An estimated loss power $P_{\text{Loss,EFIT}} = P_{\text{NBI}} + P_{\text{OHMIC}} - \frac{dW}{dt} - X$ is also shown in figure 2, where $P_{\text{NBI}}$ is the injected beam power, $P_{\text{OHMIC}}$ the product of loop voltage and plasma current, $dW/dt$ represents the change in plasma energy and $X$ the change in stored magnetic energy. There is a variation in $P_{\text{Loss,EFIT}}$ due to gas fuelling and during the H-mode due to changes in plasma stored energy between ELMs and sawteeth. The values of $dW/dt$ and $X$ are obtained from the equilibrium reconstruction code EFIT [25]. The $P_{\text{Loss}}$ required for L-H threshold measurements is equivalent to $P_{\text{Loss}} = P_{\text{Loss,EFIT}} - P_{\text{Rad}} - P_{\text{NBI,shinethrough}}$. The power threshold, $P_{th}$, is the minimum value of the $P_{\text{Loss}}$ required to cause an L-H transition. Previous studies on MAST [27] have shown that measurements from the Langmuir probes at the inner and outer strike points is a good proxy for the total power entering the scrape off layer and hence provide a direct measurement of $P_{\text{Loss}}$. The values of $P_{\text{Loss}}$ as obtained from Langmuir probe measurements, for the four beam powers measured shortly before the L-H transition are shown in table 1. These Langmuir probe measurements
measurements are used throughout the rest of the paper to estimate the $P_{\text{Loss}}$ for discharges with the various injected neutral beam powers. Since the discharge with 0.6 MW of injected beam power was close to the power threshold, the $P_{\text{th}}$ for these 400 kA discharges is estimated to be $\sim 0.48$ MW.

Previously detailed studies of power threshold on MAST [20] were performed for a 600 kA LSND discharge with slightly different shaping to the 400 kA discharges discussed here. These studies found marginal L-H dithers for an ohmic discharge and a clear transition to H-mode on injection of 0.3 MW of beam power corresponding to a $P_{\text{th},600\text{kA}} = 0.43 + /− 0.1$ MW which is in agreement within errors of the value estimated above of 0.48 MW.

It is appropriate to address the delay in L-H transition with reduced beam power at this point, since a delay in L-H transition time as observed in figure 2 due to decreased beam power is observed due to increased RMP. There is no change in $P_{\text{th}}$ dependent parameters with discharge time in these pulses. Toroidal field ($B_t$), line integral density ($n_{e,20}$) and plasma surface area ($S$) are all constant over the course of the discharges and there is no observed change in $T_e$ or $n_e$ profiles while the discharges remain in L-mode. However, there is a constant decrease in $q_{95}$ over the course of the shot from $\sim 4.8$ at 350 ms to $\sim 3.7$ at 500 ms which reduces the parallel connection length. The large aspect ratio approximation for the connection length from the midplane to the target $L_{\text{uni}} = L_{\text{uni}}$,95 reduces from 13.4 m at 350 ms to 10.3 m at 500 ms. This change occurs since the plasma major radius increases and because the outboard edge location is kept constant by the control system the minor radius decreases. The changes in major and minor radius both act to decrease $q_{95}$. Although $P_{\text{th}}$ is not directly dependent on $q_{95}$, there have been reported changes in L-H threshold with divertor leg length and hence connection length between the X-point and the target [22, 26] suggesting that shorter lengths are more favourable for H-mode access. The easier H-mode access observed later in MAST discharges is likely due to decrease in connection length from the X-point to the target due to decrease in $q_{95}$ as the discharge progresses.

### 4. Impact of $n = 6$ RMPs on L-H transition for a 400 kA discharge

The impact of varying RMP coil current on a typical discharge is shown in figure 3. This discharge has 1.5 MW of injected neutral beam power and a $P_{\text{Loss}} \sim 1.04$ MW and hence is at least a factor of 2 above the L-H power threshold. In this case RMPs are applied in an $n = 6$ configuration, with coil currents of 0.6, 1.0 and 1.4 kA. The line integral density is held constant from 300 ms and the L-H transition for all discharges occurs at a value of $\int n_{e} dl = 1.25 \times 10^{21}$ m$^{-2}$. Similar density profiles from the Thomson scattering diagnostic are observed for the no RMP, $I_{\text{RMP}} = 1.0$ kA and $I_{\text{RMP}} = 1.4$ kA discharges up to the timing of the L-H transition. No Thomson scattering data is available for the $I_{\text{RMP}} = 0.6$ kA discharge, however a
similar time evolution of the line integral density is observed from the interferometer up to the timing of the L-H transition. A particle ‘pump out’ caused by the RMPs is evidenced by an increased gas refuelling rate with increasing RMP coil current as shown in figure 3(b). Previous studies have shown that the walls of the MAST machine do not saturate during a discharge and remain pumping [28], hence the change in gas puff rate observed with RMP relates to an increased fuelling of the plasma. Once in H-mode, the gas fuelling is turned off by the feedback system. A strong increase in ELM frequency (~doubling) is observed in the discharges with applied RMP.

The impact on the timing of the L-H transition is very large with delays of ~13, 120 and 130 ms for 0.6, 1.0 and 1.4 kA respectively.

No significant difference is observed in the $n_e$ or $T_e$ profiles which could account for the change in H-mode accessibility, as shown in figures 4(a) and (e). However, there are changes to the carbon emissivity, toroidal velocity and $T_i$ as shown in figures 4(b), (c) and (f) respectively. This data is obtained from measurements of charge exchange between injected beam ions and carbon impurities [29]. Measurements of the charge exchange emission at the separatrix are not well resolved due to the instrument function and strong background emission, however, measurements a few cm inside the last closed flux surface are reliable.

An estimate of the radial electric field in the edge region of the charge exchange measurements is shown in figures 4(d) and (h). This radial electric field is given by $E_r = \frac{dP_i}{dr} - v_\theta B_\phi + v_\phi B_\theta$ and contributions from the ion pressure gradient and toroidal velocity terms are used for the results shown. The poloidal velocity contribution to $E_r$ is not known, as poloidal velocity was not measured for these discharges, however this contribution is likely to be low as previous measurements of poloidal velocities on MAST have indicated small values [30]. As the RMP intensity is increased it may be seen that the impurity density is reduced. This is understandable as the RMPs cause a particle ‘pump out’ for all species and the feedback on electron density causes increased refuelling by deuterium gas puffing. A measurement of the absolute carbon density, as shown in figure 4(g), has been obtained from RGB [31] shows a decrease in peak carbon density from $3 \times 10^{17}$ m$^{-3}$ at 1.4 kA to $1.8 \times 10^{17}$ m$^{-3}$ at 1.0 kA and 0.6 kA to $1.2 \times 10^{17}$ m$^{-3}$ at 0.0 kA. Reduced plasma velocity with increasing RMP field, as shown in figure 4(b), is typical of MAST plasmas [32]. The reduction in $T_i$ is less well understood, especially as no impact is seen on $T_e$, but could be due to the link between ion temperature and velocity. The depth of the radial electric field well, as shown for the edge in figure 4(h), decreases (becomes more positive) for increasing RMP intensity. This change of the edge radial electric field with RMP is largely due to the effects of changes in carbon temperature and density, since the toroidal velocity in this region is similar for these discharges and has a similar contribution to $E_r$.

Figure 3. Impact of increasing RMP coil intensity, in $n = 6$ configuration, on timing of the L-H transition for a 400 kA discharge with 1.5 MW of injected neutral beam power. (a) RMP coil current (b) D$_2$ gas refuelling rate in density feedback (c)–(f) D-alpha emission as measured at the midplane.
RMP for a connected double null (CDN) discharge. It should be noted that the radial electric field is the same for whichever ion species examined, however the relative contributions of the Lorentz component and pressure gradient component to that radial electric field can vary depending on the species.

5. Impact on L-H transition of different applied $n$

The impact of RMPs of different $n$ number on the transition is shown in figure 5 for a series of 400 kA plasmas. Discharges are examined with 0.9, 1.2 and 1.5 MW of NBI power, with no applied RMP and applying $n = 2$, 3, 4 and 6 perturbations, in all cases with 1.4 kA of coil current. An estimate of the energy confinement time for the no applied RMP discharges of ~30 ms is obtained from EFIT.

The results of these comparisons show that the $n = 2$ has the greatest impact on H-mode access, completely suppressing the L-H transition in the 1.5 MW discharge. These results indicate an increase in power threshold of at least 100% for these $n = 2$ discharges. The $n = 2$ RMP discharges on MAST have a much greater core plasma braking than higher $n$.'s. For comparison the toroidal rotation braking of these discharges at a time just before the L-H transition is shown in figure 6.

For the $n = 3$ and 4 cases with 1.5 MW of injected power there is a significant delay in the L-H transition time, even though at this $P_{\text{NBI}}$ the $P_{\text{loss}}$ is at least a factor of 2 above the $P_{\text{th}}$ required for H-mode access with no applied RMP. Decreasing the beam power to 1.2 MW, such that the discharges are at least a factor of 1.6 above the no RMP $P_{\text{th}}$, the timing of the L-H transition is delayed by ~3$T_\text{E}$. No sustained H-mode access is obtained for shots in $n = 3$ and $n = 4$ at NBI powers of 0.9 MW. This implies an increase in power threshold of at least 20% above the no RMP $P_{\text{th}}$.

Application of RMPs with the same RMP coil current in an $n = 6$ configuration causes a larger impact on the L-H transition than $n = 3$, 4. For the 1.5 MW discharge the timing of the L-H transition is delayed by ~3$T_\text{E}$, although once the transition occurs the H-mode is stable. For the 1.2 MW discharge a short H-mode period is obtained followed closely by a back transition, indicating that for this level of applied RMP the plasma is close to its L-H power threshold. Hence the power threshold is increased by at least 60% at this RMP field for $n = 6$ discharges.

Expressing the increased power requirements to access H-mode in terms of injected power, an increase of 50% in external heating is required for $n = 3$ and 4 discharges and an increase of 100% in external heating is required for $n = 6$ discharges. Comparing in terms of power through the separatrix, the respective values of 20 and 60% are considerably lower. This is due to the relative magnitudes of radiated power, ohmic heating power and neutral beam shine through fraction.

The figure of merit for ELM mitigation is the achieved increase in ELM frequency due to the RMP versus the cost, which is the reduction in energy confinement due to the RMP induced particle pump out. The application of 1.4 kA of RMP coil current for $n = 3$, 4 and 6 results in an increase from $f_{\text{ELM}} \sim 25$ Hz to $f_{\text{mitigated}} \sim 65$ Hz at 1.5 MW, and from $f_{\text{ELM}} \sim 15$Hz to $f_{\text{mitigated}} \sim 55$Hz in the 1.2 MW case. Both sets of mitigated discharges show a drop in energy confinement of ~20–30%.

The results from pulses already shown in figure 5, as well as from further discharges with RMP currents of 0.6 and 1.0 kA are shown in figure 7. Each point in this figure represents either a discharge that remained in L-mode, symbolised by a diamond, or transitioned to H-mode, symbolised by
R Scannell et al 7

a circle. ERGOS [17] vacuum simulations were run for the case of 1.4 kA in the RMP coils to determine \( b_{\text{res}} \) and \( \sigma_{\text{Chirikov}} \) for these discharges. The results of these runs are shown in figure 8. The top row of figure 7 shows discharges as a function of injected neutral beam power and current in the RMP coils. The center row shows the same discharges in terms of \( P_{\text{Loss}}/P_{\text{th}} \) and \( b_{\text{res}} \). The final row shows the discharges in terms of \( P_{\text{Loss}}/P_{\text{th}} \) and \( \Delta \sigma_{\text{Chirikov}} > 1 \).

The magnitude of \( b_{\text{res}} \) is \([0.78, 0.66, 0.81, 0.85] \times 10^{-3}\) at \( \Psi = 0.95 \) for \( n = [2, 3, 4, 6] \) respectively. There is a large \( n = 2 \) intrinsic field component, taking this into account \( b_{\text{res}} = 0.94 \times 10^{-3} \) at \( \Psi = 0.95 \) for \( n = 2 \). The relative impact of \( n = 3, 4 \) and 6 on the L-H transition may be compared using similar regions of \( b_{\text{res}} \) shown as the grey boxes of figures 7(d)–(f). This shows that for the same \( b_{\text{res}} = n = 6 \) RMP has a greater impact on the L-H power threshold and also indicates that \( n = 3 \) may have a slightly higher impact than \( n = 4 \).

For extrapolation to future devices it is important to determine how the power threshold will scale. A study presented in [18] has shown that the mitigated ELM frequency increases linearly above some minimum \( b_{\text{res}} \) value. In particular that study showed that for the \( n = 4 \) case the ELM frequency is the same as an unmitigated discharge at \( b_{\text{res}} \approx 0.5 \times 10^{-3} \) and increases rapidly such that \( f_{\text{mitigated}} \approx 3 \times f_{\text{natural}} \) at \( b_{\text{res}} \approx 1.0 \times 10^{-3} \). The increase in power thresholds for \( n = 4 \) RMP at both \( I_{\text{ELM}} = 1.0 \) kA and \( I_{\text{ELM}} = 1.4 \) kA are shown in figures 7(b) and (e). The L-H transition is suppressed at \( b_{\text{res}} \approx 0.85 \times 10^{-3} \) when \( P_{\text{Loss}} = 1.2 \times P_{\text{th}} \), however, the L-H transition occurs at the same power level when the perturbed field is reduced to \( b_{\text{res}} \approx 0.6 \times 10^{-3} \). These results indicate that there is a minimum threshold in the perturbation amplitude.
in $b_{res}$, below which there is little increase in power threshold and above which the power threshold increases quite rapidly. From figures 7(g)–(i) a similar minimum threshold exists in $\Delta_{\sigma,\text{Chirikov}} > 1$ above which $P_{\text{loss}}/P_{\text{threshold}}$ increases rapidly. The implication of this is that if a large ELM mitigation is required, such as a factor of 10, to satisfy material lifetime constraints for plasma facing components a very large increase in L-H power threshold could result.

**Figure 7.** Map of discharges showing impact of RMP on H-mode accessibility. Circles indicate discharges that did transition to H-mode, irrespective of the delay in L-H transition time. Diamonds show discharges that remained in L-mode. (a)–(c) Injected neutral beam power versus RMP coil current for $n = 3, 4, 6$ (d)–(f) Estimated $P_{\text{loss}}$ normalised to $P_{\text{threshold}}$ versus $b_{res}$. A region of constant $b_{res}$ is highlighted across the three ‘$n$’ numbers for comparison. (g)–(i) Estimated $P_{\text{loss}}$ normalised to $P_{\text{threshold}}$ versus the width of region in $\Psi_{\text{pol}}$ for which the Chirikov parameter is greater than 1 ($\Delta_{\sigma,\text{Chirikov}} > 1$).

**Figure 8.** (a) Chirikov parameter profile and (b) $b_{res}$ profile for shots with 1.4 kA in the RMP coils. The $n = 2$ value shown includes the intrinsic error field.
6. Conclusions

Application of RMP to MAST discharges close to the L-H power threshold delays the L-H transition at low applied field and prevents of the transition at high field. It has been shown that the RMPs increase the radial electric field at the edge and this is likely how they increase the power threshold. The delay in transition time is thought to occur because $L_q$ decreases during the discharge (due to changing $q_{95}$) increasing H-mode accessibility.

In order to quantify the increased power threshold due to RMP, discharges where the L-H transition is prevented due to applied RMP are compared with the determined power threshold for no applied RMP discharges. The particular case of a 400 kA lower single null discharge with a $b_{\text{resr}}$ sufficient to cause a mitigated frequency of $f_{\text{ELM}}/f_{\text{Natural}} \sim 3$ was used as a test case. Varying the toroidal perturbation of the applied field the required neutral beam power for H-mode access was 0.9 MW for $n = 3$ and 4, 1.2 MW for $n = 6$ and >1.5 MW for $n = 2$ compared with <0.6 MW for no applied RMP. Expressed in power threshold using estimates of $P_{\text{loss}}$ from Langmuir probe data, this corresponds to increases of at least 20% for $n = 3$ and 4, 60% for $n = 6$ and 100% for $n = 2$.

The power threshold required increases with applied field above a certain minimum value, similar to the trend observed for increase of ELM frequency with RMP. The combination of these scalings implies that if large mitigation factors are required on future devices to satisfy either the material lifetime constrains of plasma facing components or to prevent impurity accumulation then large increases in external heating power will be required to ensure H-mode access. To put these results in context, however, it should be noted that a strategy does exist whereby H-mode access can be obtained without RMP or at low RMP intensity, subsequently allowing the increase of RMP after H-mode is obtained. This strategy could be used to alleviate the increased external heating power requirements due to RMP. If the requirement for high ELM frequency is driven by the need to prevent impurity accumulation, this may be offset by reduced impurity density due to increased RMP transport.

Acknowledgments

This work was funded by the RCUK Energy Programme under the grant EP/I501045. To obtain further information on the data and models underlying this paper please contact PublicationsManager@cefe.ac.uk. The views expressed herein do not necessarily reflect those of the European Commission.

References

[1] Loarte A et al 2007 Nucl. Fusion 47 S203–63
[2] Evans T E et al 2008 Nucl. Fusion 48 024002
[3] Suttrop W et al 2011 Plasma Phys. Control. Fusion 53 124014
[4] Jeon Y M et al 2012 PRL 109 035004
[5] Kirk A et al 2009 Plasma Phys. Control. Fusion 51 065016
[6] Liang Y et al 2007 PRL 98 265004
[7] Liang Y et al 2013 Nucl. Fusion 53 073036
[8] Sips A C C et al 2008 Plasma Phys. Control. Fusion 50 124028
[9] Ryter F et al 2013 Nucl. Fusion 53 113003
[10] Doyle E J et al 2007 Nucl. Fusion 47 S18–127
[11] Neu R et al 2013 J. Nucl. Mater. 438 S34
[12] Maggi C 2012 Proc. 39th EPS Conf. on Plasma Physics (Stockholm Sweden 2012)
[13] Gohil P et al 2011 Nucl. Fusion 51 103020
[14] Ryter F et al 2012 Nucl. Fusion 52 114014
[15] Kaye S M et al 2011 Nucl. Fusion 51 113019
[16] Kirk A et al 2011 Plasma Phys. Control. Fusion 53 065011
[17] Nardon E et al 2007 J. Nucl. Mater. 363 1071
[18] Kirk A et al 2013 Nucl. Fusion 53 043007
[19] Ryter F et al 2002 Plasma Phys. Control. Fusion 44 A415–21
[20] Meyer H et al 2004 Plasma Phys. Control. Fusion 46 A291–8
[21] Meyer H et al 2005 Plasma Phys. Control. Fusion 47 843–67
[22] Meyer H et al 2008 Plasma Phys. Control. Fusion 50 015005
[23] Stammers K et al 2006 Nucl. Instrum. Methods Phys. Res. A 562 521
[24] Van Zeeland M A et al 2014 Plasma Phys. Control. Fusion 56 015009
[25] Lao L L et al 1985 Nucl. Fusion 25 1611
[26] Andrew Y 2004 Plasma Phys. Control. Fusion 46 A87–93
[27] Kirk A et al 2004 Plasma Phys. Control. Fusion 46 551–72
[28] Huang J et al 2010 Plasma Phys. Control. Fusion 52 075012
[29] Conway N et al 2006 Rev. Sci. Instrum. 77 10F131
[30] Field A et al 2009 Plasma Phys. Control. Fusion 51 105002
[31] Patel A et al 2015 Multi colour high definition imaging in the mega ampere spherical tokamak Rev. Sci. Instrum. in preparation
[32] Kirk A et al 2013 Plasma Phys. Control. Fusion 55 015006
[33] Conway G et al 2011 Phys. Rev. Lett. 106 065001
[34] Temain P et al 2010 Plasma Phys. Control. Fusion 52 075017