

# Edge stability and transport control with resonant magnetic perturbations in collisionless tokamak plasmas

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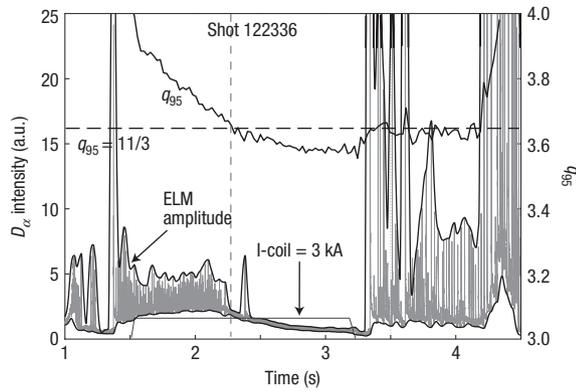
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A critical issue for fusion-plasma research is the erosion of the first wall of the experimental device due to impulsive heating from repetitive edge magneto-hydrodynamic instabilities known as ‘edge-localized modes’ (ELMs). Here, we show that the addition of small resonant magnetic field perturbations completely eliminates ELMs while maintaining a steady-state high-confinement (H-mode) plasma. These perturbations induce a chaotic behaviour in the magnetic field lines, which reduces the edge pressure gradient below the ELM instability threshold. The pressure gradient reduction results from a reduction in the particle content of the plasma, rather than an increase in the electron thermal transport. This is inconsistent with the predictions of stochastic electron heat transport theory. These results provide a first experimental test of stochastic transport theory in a highly rotating, hot, collisionless plasma and demonstrate a promising solution to the critical issue of controlling edge instabilities in fusion-plasma devices.

**M**aximizing the fusion power production in toroidally symmetric magnetic confinement devices (tokamaks<sup>1,2</sup>) requires high-confinement (H-mode) plasma conditions that have high edge-plasma pressures. A ubiquitous feature of these high edge pressure, steady-state, H-mode tokamak plasmas is repetitive instabilities known as ‘edge-localized modes’ (ELMs), which release a significant fraction of the thermal energy of the plasma to the first wall of the device. These instabilities are a class of ideal magneto-hydrodynamic modes produced in a high-pressure-gradient region at the plasma edge (known as the ‘pedestal’) where pressure-gradient-driven ‘ballooning’ modes can couple to current-density-driven ‘peeling’ modes<sup>3</sup>. ELMs provide a natural transport process that controls the core plasma density and edge impurity ion penetration, and they also represent a significant concern for burning-plasma devices, such as the International Tokamak Experimental Reactor (ITER)<sup>2,4</sup>. On the basis of an extensive multi-machine ELM database, it is well known that the impulsive energy released during an ELM increases with decreasing electron pedestal collisionality<sup>5</sup>  $\nu_e^* \propto n_e^{\text{ped}} (T_e^{\text{ped}})^{-2}$ . As burning plasmas require high electron pedestal temperatures ( $T_e^{\text{ped}}$ ) at relatively high electron pedestal densities ( $n_e^{\text{ped}}$ ) to achieve significant fusion power-gain factors,  $Q \geq 10$ , they must operate below  $\nu_e^* = 0.1$ . In this case, each ELM is expected to expel up to 20% of the pedestal energy over a time interval of a few hundred microseconds. If allowed to reach plasma-facing wall components, energy impulses of this magnitude will cause increased erosion of plasma-facing components and will significantly reduce their lifetime<sup>5,6</sup>. Thus, controlling ELMs by replacing the energy impulses with an equivalent but more continuous transport process is a high-priority issue for tokamak-fusion research.



**Figure 1** ELM response to an applied magnetic perturbation. Shown here are the evolution of: the lower divertor  $D_\alpha$  intensity,  $q_{95}$  the safety factor at the 95% normalized poloidal flux surface, and the applied I-coil current in DIII-D discharge no. 122336.

A particularly appealing ELM control approach in low- $\nu_e^*$  plasmas is based on the concept of using an edge stochastic magnetic field to increase the electron thermal diffusivity  $\chi_e$  across the outer pedestal region, thus reducing the electron pressure gradient  $\nabla p_e$  and stabilizing peeling–ballooning (P–B) modes. Stochastic layers are created by adding small resonant magnetic perturbations (RMPs) to the equilibrium magnetic field using external coils. Experiments in high-collisionality ( $\nu_e^* \geq 1.0$ ), low-confinement, plasmas have demonstrated that  $\chi_e$  can be increased significantly across an edge stochastic layer<sup>7–9</sup>. Theoretically,  $\chi_e$  is predicted to scale as  $\nu_{Te} D_m$  in collisionless plasmas<sup>10</sup>, where  $\nu_{Te}$  is the electron thermal velocity and  $D_m$  is a magnetic diffusion coefficient. In the quasi-linear regime,  $D_m$  is proportional to the square of the normalized magnetic perturbation  $\delta b_r^{(m/n)} B_\phi^{-1}$ . Here,  $\delta b_r^{(m/n)}$  is the radial magnetic perturbation field where  $m$  and  $n$  are the poloidal and toroidal mode numbers respectively, and  $B_\phi$  is the toroidal magnetic field on axis (a resonance occurs when the so-called ‘safety factor’  $q = m/n$ , the ratio of the number of toroidal turns  $m$  to poloidal turns  $n$  around the torus, is a rational number<sup>2</sup>).

Previous experiments in high- $\nu_e^*$ , low-confinement, plasmas have demonstrated that  $\nabla T_e$  is reduced across the outer region of a strong stochastic layer and increased across the inner stochastic region<sup>7</sup>. In addition, edge resonant magnetic perturbations with  $m = 12–20$  and  $n = 4$  were used in the JFT-2M tokamak to trigger small ELMs in ELM-free H-modes<sup>11</sup> and to increase the frequency of small ELMs in the COMPASS-D tokamak (with  $m = 4, 5$  and  $n = 1$  perturbations)<sup>12</sup>. In the DIII-D tokamak, edge-resonant perturbations with  $n = 3$  and  $9 \leq m \leq 14$  were previously used to suppress large ELMs in high- $\nu_e^*$  plasmas without altering the plasma confinement<sup>1,13–16</sup>. These results motivated the exploration of low-collisionality RMP pedestal and ELM control techniques in the DIII-D tokamak where high electron and ion pedestal temperatures ( $T_e^{\text{ped}}, T_i^{\text{ped}} \geq 1$  keV) are regularly obtained.

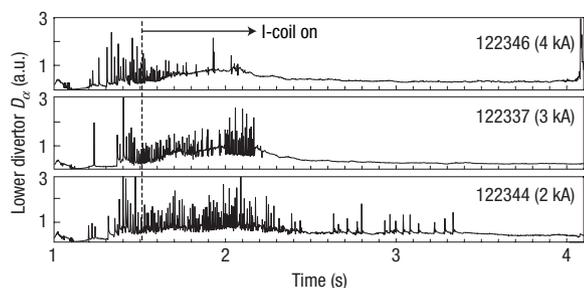
Here, we report results from the first  $n = 3$  edge RMP ELM control experiments in low-collisionality  $0.04 \leq \nu_e^* \leq 0.12$ , ITER-relevant, DIII-D plasmas. These experiments resulted in long ELM-free H-modes,  $\Delta t = 2,550$  ms (17 energy confinement times), with stationary densities and radiated power levels. A detailed P–B analysis of these RMP-assisted ELM-free H-modes shows that they operate below the peeling stability boundary and that ELMs are stabilized when RMPs reduce the edge pressure gradient  $\nabla p$ ,

primarily through a modification in the pedestal density rather than the pedestal temperature. The observation that the RMP field causes a larger change in the edge particle balance (that is, changes in the balance between outward particle transport and edge particle sources and sinks) rather than in the thermal transport across the pedestal is both surprising and theoretically challenging.

As in previous high- $\nu_e^*$  ( $\sim 1$ ) RMP ELM control experiments<sup>13–16</sup>,  $n = 3$  magnetic perturbations are produced by the DIII-D I-coil located inside the vacuum vessel but outside the plasma. However, there are significant differences in the poloidal mode spectrum used in the high- $\nu_e^*$  experiments versus that used in the low- $\nu_e^*$  experiments discussed here. In the high- $\nu_e^*$  case, the I-coil was configured to produce small magnetic islands (isolated structures on mode resonant surfaces) across the pedestal with a relatively thin stochastic boundary<sup>15</sup>. Although this resulted in good ELM suppression with no significant change in the pedestal profiles or plasma confinement, some intermittent ELM events remained in most cases. In these high- $\nu_e^*$  cases, ELMs seem to be stabilized by an increase in small transport events near the plasma edge<sup>14</sup>. Conversely, in the low- $\nu_e^*$  experiments discussed here, the I-coil is configured to produce a highly stochastic layer covering the entire pedestal region, with relatively small remnant magnetic islands. Here, the magnitude of the RMP mode spectrum across the pedestal ( $m/n = 11/3, 12/3$  and  $13/3$ ) is increased by an order of magnitude compared with the high- $\nu_e^*$  low-RMP case.

In both the low- and high- $\nu_e^*$  experiments, ELMs are only eliminated when the perturbation spectrum of the coil matches an edge resonance condition<sup>17</sup> determined by the helical pitch of the equilibrium magnetic field lines (the edge safety factor  $q = m/n$ ). Figure 1 shows the ELM response to a 3-kA I-coil pulse in a lower single null poloidally diverted plasma (a plasma with a null in the poloidal magnetic field located at the bottom of the discharge<sup>1</sup>). In this discharge, the lower DIII-D cryopump is used to pump the plasma and obtain low, ITER-relevant, pedestal collisionalities. Here, 3 kA corresponds to a normalized  $m/n = 11/3$  perturbation  $\delta b_r^{(11/3)} B_\phi^{-1} = 2.6 \times 10^{-4}$ , where  $B_\phi = 2.0$  T. Initially, while the safety factor at the 95% ( $q_{95}$ ) normalized poloidal magnetic flux ( $\psi_N$ , an effective radial coordinate<sup>18</sup>) surface  $\psi_N = 0.95$  is above 11/3, the RMP reduces the ELM amplitude and increases the ELM frequency from  $\sim 25$  Hz to  $\sim 200$  Hz. As  $q_{95}$  approaches the 11/3 resonance condition, ELMs are completely eliminated for the remainder of the I-coil pulse. After the I-coil current is switched off, large 25–50 Hz ELMs return once the pedestal profile recovers and  $\nabla p$  exceeds the P–B stability limit. Additionally, a threshold for ELM suppression is found in the neutral beam injected (NBI) heating power  $P_{\text{NBI}} \geq 4.0$  MW (NBI powers of 10.0 MW have been used with no indication of an upper power limit). There is also a threshold in the RMP amplitude as shown in Fig. 2. Here, three RMP amplitudes ranging from  $\delta b_r^{(11/3)} B_\phi^{-1} = 1.7 \times 10^{-4}$  (with an I-coil current of 2 kA) to  $\delta b_r^{(11/3)} B_\phi^{-1} = 3.3 \times 10^{-4}$  (with 4 kA) have been used. The ELM response at each perturbation level from high to low is shown in Fig. 2a–c respectively. As seen in Fig. 2c, some ELMs remain at 2 kA but at 3 kA (Fig. 2b) the ELMs are completely eliminated once  $q_{95}$  crosses 11/3. At 4 kA (Fig. 2a), ELMs are more strongly affected at higher  $q_{95}$  values but not completely eliminated until reaching  $q_{95} = 11/3$ . This indicates a slight increase in the width of the safety factor resonance with increasing perturbation amplitude.

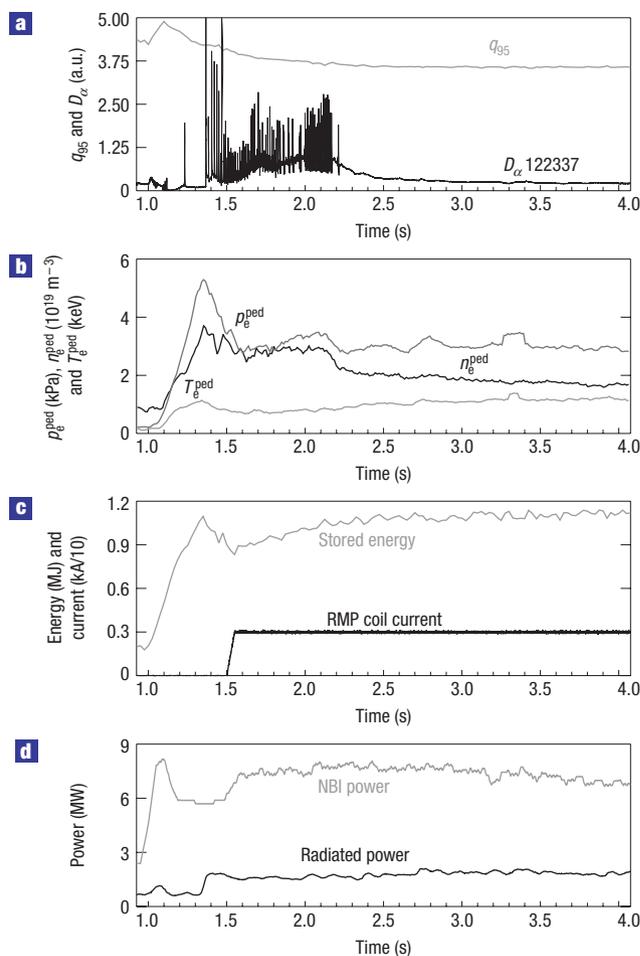
During the initial off-resonance phase of the RMP pulse ( $q_{95} > 11/3$ ) an increase in energy transport caused by small, high frequency, ELMs commands the normalized plasma pressure ( $\beta_N$ ) feedback system to increase the NBI power by  $\sim 15–20\%$ . Once the  $q_{95}$  resonance condition is satisfied, these small ELMs disappear, leaving the plasma in a very quiet state (Fig. 3a), and the pedestal density  $n_e^{\text{ped}}$  begins to fall while  $T_e^{\text{ped}}$  continues to increase



**Figure 2** Changes in the ELM response with increasing magnetic perturbation levels. Divertor  $D_\alpha$  emission (particle recycling light) with I-coil currents of: 4 kA, 3 kA and 2 kA, respectively. In these discharges, the I-coil current typically remains constant until 5 s when it is switched off owing to hardware limitations on the length of the plasma discharge.

slowly (Fig. 3b). The electron pedestal pressure ( $p_e^{\text{ped}}$ ; Fig. 3b) drops initially following the suppression of the small ELMs and remains relatively constant throughout the remainder of the RMP pulse. The thermal energy content of the plasma (Fig. 3c) increases slowly during the rapid ELMing phase due to the increased NBI power and reaches a relatively stationary level once the small ELMs disappear. In addition, the total power radiated from the plasma remains constant throughout the ELM-free phase (Fig. 3d). During the rapid ELMing phase at 1.9 s, the electron density on axis is  $n_{e0} = 5.2 \times 10^{19} \text{ m}^{-3}$  and the central electron temperature is  $T_{e0} = 3.7 \text{ keV}$ . At 3.5 s with no ELMs,  $n_{e0} = 3.8 \times 10^{19} \text{ m}^{-3}$  and  $T_{e0} = 4.0 \text{ keV}$ . This change in  $n_{e0}$  along with the entire density profile is indicative of a dramatic change in the particle balance once the ELMs are suppressed. In contrast, the global energy confinement time ( $\tau_E$ ) shows a modest increase from 130 ms at 1.9 s to 147 ms at 3.5 s. Although the ELM-free properties of these discharges are similar in some respects to quiescent H-modes in DIII-D<sup>19</sup>, they do not have edge harmonic oscillations<sup>19</sup>, which are coherent modes thought to be responsible for the particle transport out of the pedestal during quiescent H-modes.

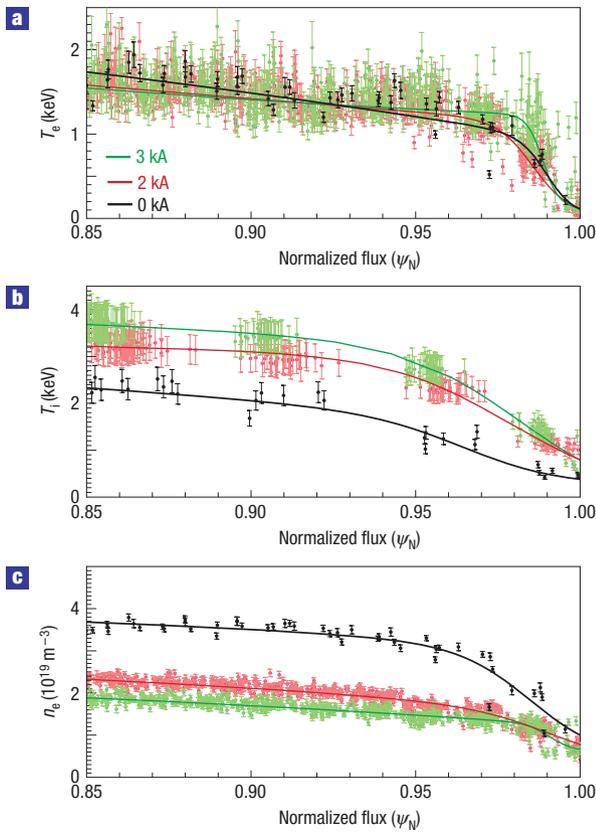
Changes in the edge-plasma profiles during the RMP ELM-free phase are indicative of a significant alteration in the particle balance with a relatively small change in the energy transport and are qualitatively inconsistent with stochastic transport theory<sup>10</sup>. Figure 4 shows how the edge  $T_e$ ,  $T_i$  and  $n_e$  profiles change, when averaged over a 600-ms time window, during the ELM-free phase with I-coil currents of 2 and 3 kA compared with an equivalent window during an ELMing phase with no I-coil current just before the onset of an ELM (the 0-kA case). The  $T_e$  profile (Fig. 4a) seems to decrease from  $\psi_N = 0.85$  out to just beyond  $\psi_N = 0.93$  and increases out to the top of the pedestal with the RMP. Comparing the 2-kA, marginally stable, case with the 0-kA case, we see that the electron pedestal temperature gradients  $\nabla T_e^{\text{ped}}$  are a good match to within the experimental uncertainty. As the coil current is increased to 3 kA we see the formation of a higher/narrower pedestal structure compared with the other two profiles (that is, an increase in  $\nabla T_e^{\text{ped}}$  and a corresponding decrease in  $\chi_e$  in the region  $0.99 \leq \psi_N \leq 1.0$ ). This is inconsistent with the expectation from stochastic transport theory<sup>10</sup> that  $\chi_e$  should increase significantly across a broad ( $\Delta\psi_N \approx 0.1$ ) stochastic layer induced by the RMP. No profiles have been found during these experiments with the expected  $\nabla T_e^{\text{ped}}$  decrease and a corresponding increase in  $\chi_e$  over the last 1–2% in  $\psi_N$ . In contrast, we note that in the region near the top of the pedestal the profile is quite flat compared with the unperturbed case (particularly with 3 kA). This may indicate that



**Figure 3** The value of the safety factor at the 95% magnetic flux surface ( $q_{95}$ ) influences the ELM response to the RMP. **a**, ELMs are seen as spikes in the divertor  $D_\alpha$  emission (particle recycling light), which disappear as  $q_{95}$  crosses 11/3. **b**, The electron pedestal pressure, density and temperature. **c**, The energy content of the plasma (stored energy) and the RMP current amplitude. **d**, The injected neutral beam heating power (NBI power) and total power radiated from the plasma.

quasi-linear diffusion theory is qualitatively more applicable in that region of the plasma than in the steep pedestal gradient region. In addition, as shown in Fig. 4b, the  $T_i$  profile increases across the entire plasma edge and  $\nabla T_i^{\text{ped}}$  increases just inside the unperturbed separatrix (the unperturbed separatrix is the 2D poloidal boundary that separates closed magnetic field lines inside from field lines that hit plasma-facing components outside). These changes in the pedestal  $T_e$  and  $T_i$  profiles are in sharp contrast to the  $n_e$  profile behaviour shown in Fig. 4c. Here, the density at the unperturbed separatrix location  $n_{e,\text{sep}}(\psi_N = 1.0)$  decreases significantly with the I-coil on compared with the zero current case, and the density gradient  $\nabla n_e$  is reduced near  $\psi_N = 1.0$  along with the radial extent of  $\nabla n_e$  (that is, the ‘pedestal’ is narrower).

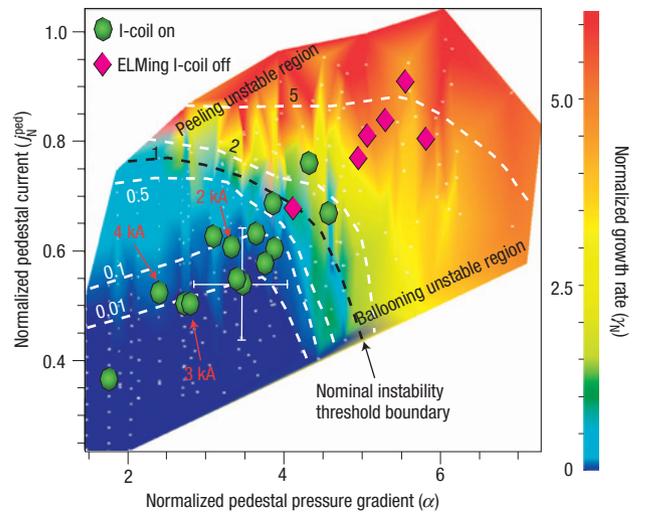
In these experiments we consistently find that, within experimental uncertainty, RMP ELM-free discharges are stable to P–B modes, whereas ELMing discharges become unstable to P–B modes just before an ELM occurs. Profile data such as those in Fig. 4 are used in a 1D stability code (ELITE<sup>3,20</sup>) to evaluate the P–B mode stability for a rather extensive collection of ELMing and RMP-assisted ELM-free discharges. These stability calculations are based on accurate global reconstructions of full plasma profiles



**Figure 4** Changes in the edge-plasma profiles with various magnetic perturbation levels. The edge profiles of: **a**, electron and **b**, ion temperature and **c**, electron density with no I-coil just before the onset of an ELM (black, no. 122336), 2 kA (red, no. 122344) and 3 kA (green, no. 122337) versus normalized poloidal magnetic flux ( $\psi_N$ ). The edge pedestal beyond  $\psi_N > 0.95$  is most clearly seen in the  $T_e$  profile for the 3 kA case. The solid curves are fits to the data points showing the average profiles over the data window. Error bars representing uncertainties due to photon statistics (statistical fluctuations in the signal and observed background noise) in the Thomson scattering measurements are shown on the individual data points.

along with a broad range of unstable mode numbers ( $n = 5\text{--}30$ ). We represent these non-local stability results in a simplified manner in Fig. 5. Here, the global experimental profiles are characterized by representative local values. Figure 5 shows that in RMP-assisted ELM-free discharges (green ellipses) the normalized growth rate resides inside the stable region when the error bars on the data are taken into consideration. On the other hand, discharges with ELMs (magenta diamonds) consistently reside outside the stability boundary in Fig. 5. This figure also demonstrates that RMP-assisted ELM-free discharges exist in the P–B stable region (and can be deeply stable for example, with increasing RMP current as indicated by the red I-coil currents in Fig. 5), whereas ELMing discharges become unstable to P–B modes before ELMs are observed.

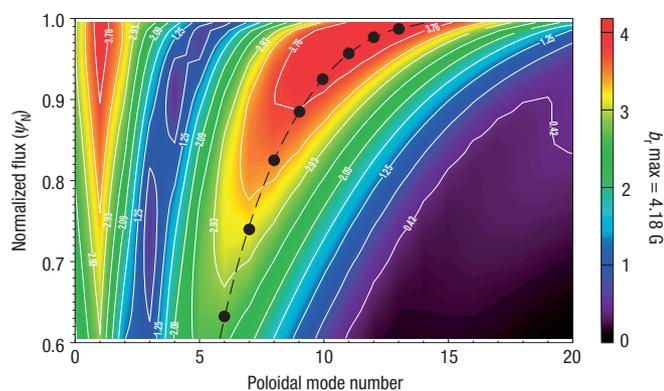
Although the precise amplitude of the RMP perturbations on resonant magnetic surfaces across the pedestal is difficult to establish in a rotating, high-pressure plasma (due to uncertainties such as shielding or amplification produced by the plasma response to the perturbation), an estimate of the vacuum magnetic field perturbation spectrum  $\delta b_r^{(m/n)}$  is useful for interpreting changes observed in the edge transport when the RMP is applied. A contour plot of a typical poloidal mode spectrum for the  $n = 3$  components



**Figure 5** ELM stability diagram. Normalized P–B mode growth rates  $\gamma_N \equiv \gamma / 0.5\omega_{*e}$  (where  $\gamma$  is the P–B growth rate and  $\omega_{*e}$  is the electron drift frequency across the magnetic field referred to as the diamagnetic drift frequency) for six ELMing cases (magenta diamonds) just before the onset of an ELM and 14 RMP-induced ELM-free (green ellipses) cases. The stability calculations are non-local, sensitive to the global equilibrium profiles, and are represented in terms of local equilibrium quantities to allow simple comparisons. Here,  $\gamma_N$  is plotted as a function of the maximum value of the normalized pedestals pressure gradient  $\alpha = -(2\mu_0 / (2\pi)^2) \partial V / \partial \psi (V / 2\pi^2 R_0) \partial \rho / \partial \psi$  (where  $V$  is the plasma volume,  $\rho$  is the pressure,  $\psi$  is the poloidal magnetic flux and  $R_0$  is the major radius of the plasma) and a characteristic pedestal current density  $j_N^{\text{ped}}$ , which is taken to be the peak value of the parallel current in the pedestal normalized by the average parallel current in the pedestal. Representative error bars, denoting one standard deviation, are shown on the data point at  $\alpha = 3.4$  and  $j_N^{\text{ped}} = 0.53$ . The colour bar on the right shows the value of  $\gamma_N$  for each experimental profile modelled with the stability code.

of  $\delta b_r^{(m/n)}$  used in these experiments is shown in Fig. 6. The dashed black curve shows the location, along the contours, of the mode resonant surfaces. Discrete harmonic resonances are indicated by black dots satisfying the condition  $m = nq(\psi_N)$ . We note that for the I-coil configuration used in these low- $\nu_e^*$  discharges the pedestal resonances,  $11 \leq m \leq 13$ , all have roughly equal amplitudes near the maximum value of the spectrum ( $\sim 4.2$  G).

Using the data from Fig. 6 we estimate the stochastic magnetic field diffusivity based on quasi-linear theory<sup>8,10,21</sup> as  $D_{m,n}^{\text{ql}}(m) = \pi R_0 \sum_{m=11-13} q_{m,n} (\delta b_r^{(m/n)} B_T^{-1})^2$  ( $m = 3.5 \times 10^{-6}$  m). Thus, for  $T_e^{\text{ped}} = 1.1$  keV,  $\nu_{Te} = 1.4 \times 10^7$  ( $\text{m s}^{-1}$ ) the cylindrical quasi-linear thermal diffusivity is  $\chi_{m,n}^{\text{ql}}(\text{m}^2 \text{s}^{-1}) = \nu_{Te} D_{m,n}^{\text{ql}}(\text{m}^2 \text{s}^{-1}) = 49 \text{ m}^2 \text{ s}^{-1}$ . Using  $D_{m,n}^{\text{ql}}$  and the ion sound speed<sup>22</sup>  $c_s(\text{m s}^{-1}) = \sqrt{(T_e + \gamma_i T_i) / m_i}$  ( $\text{m s}^{-1}$ ) =  $5.5 \times 10^5$  ( $\text{m s}^{-1}$ ), where  $T_i^{\text{ped}} = 1.8$  keV,  $\gamma_i = 3$  and  $m_i$  is the mass of the deuterium ions used in these plasmas, the stochastic particle diffusivity across the pedestal is  $1.9 \text{ m}^2 \text{ s}^{-1}$ . Then, using the electron heat flux crossing  $\psi_N = 0.95$  ( $q_e = P_e / A_{\psi_{95}}$ , where  $P_e = 2.4$  MW is the heating power absorbed by the electrons and  $A_{\psi_{95}} = 49.3 \text{ m}^2$  is the surface area at  $\psi_N = 0.95$ ) we find  $\chi_e^{\text{exp}} = -q_e / n_e \nabla T_e = 2.8 \text{ m}^2 \text{ s}^{-1}$  based on the 3-kA  $T_e$  profile shown in Fig. 4a and  $n_e$  from Fig. 4c. In the high-gradient region where  $\psi_N = 0.985$ , we find  $\chi_e^{\text{exp}} = 0.1 \text{ m}^2 \text{ s}^{-1}$ . Thus, there is a significant difference between the quasi-linear and experimental thermal diffusivity in the high-gradient region, where  $\chi_{m,n}^{\text{ql}} / \chi_e^{\text{exp}} \sim 500$ , whereas just inside the top of the pedestal at  $\psi_N = 0.95$  this difference is reduced to  $\chi_{m,n}^{\text{ql}} / \chi_e^{\text{exp}} \sim 18$  which is a rather modest difference given the



**Figure 6** Contour plot of the magnetic perturbation spectrum. The Fourier amplitude of the  $n = 3$  magnetic field from a 2 kA I-coil current in plasma discharge 122344 as a function of poloidal mode number and normalized poloidal flux  $\psi_N$ , and includes perturbations from all measured sources of field errors in DIII-D. White contour lines are drawn at each 10% change in amplitude and  $m = nq(\psi_N)$  resonances (black circles) lie along a ridge in the contours of the perturbing field. The colour bar on the right shows the amplitude scale in Gauss.

uncertainties in the experimental and quasi-linear estimates. A similar estimate of the thermal diffusivity with no I-coil current gives  $0.8 \text{ m}^2 \text{ s}^{-1}$  at  $\psi_N = 0.95$  and transport modelling using  $\chi_e$  as a free parameter in a 2D fluid code (UEDGE<sup>23</sup>) results in a reasonably good match with the black (0 kA)  $T_e$  profile shown in Fig. 4a inside  $\psi_N = 0.95$  when  $\chi_e = 1.4 \text{ m}^2 \text{ s}^{-1}$ . Although estimates of the particle diffusivity ( $D_{\perp e}$ ) are more difficult to assess because of uncertainties in local sources and sinks, UEDGE modelling, with zero I-coil current, gives a reasonable match to the experimental data with  $D_{\perp e} = 0.1 \text{ m}^2 \text{ s}^{-1}$ . This increases to  $D_{\perp e} = 0.2 \text{ m}^2 \text{ s}^{-1}$  with an I-coil current of 3 kA. These results indicate that in the pedestal  $\chi_e$  is several orders of magnitude smaller than expected based on quasi-linear theory and seems to decrease slightly during the 3-kA RMP pulse. Thus, stochastic transport theory alone cannot explain the experimental results.

The experimental data is also inconsistent with predictions of the RMP screening level due to the toroidal rotation of the plasma. During the initial part of the RMP pulse the pedestal safety factor profile is well above the optimal value required for a strong stochastic layer, that is, the resonance curve in Fig. 6 lies to the right of the spectral peak reducing the amplitude of the resonant  $\delta b_r^{(m/n)}$  components. Then, as the pedestal safety factor profile approaches the optimal resonant condition the small high-frequency ELMs are eliminated and increasing stochastic transport compensates the loss of ELM-driven transport. Simultaneously, the average toroidal rotation of the edge plasma  $\Omega_\phi$  just inside the unperturbed separatrix increases by  $\sim 3$  kHz. On the basis of magnetic shielding theory<sup>24</sup>, this change in  $\Omega_\phi$  should reduce  $\delta b_r^{(m/n)} B_\phi^{-1}$  by about a factor of 100. A reduction of this magnitude would imply that the RMP fields are unable to create a stochastic layer because the widths of the resulting magnetic islands would be significantly smaller than their separation and they will not overlap. Thus, rotational shielding, in its present form, contradicts several experimental observations: the dramatic reduction in  $n_e$ , the increase in  $\Omega_\phi$  across the pedestal and the increase in  $\chi_e$  at  $\psi_N \leq 0.95$  when  $q_{95}$  crosses 11/3 as well as the resonant character of the ELM suppression.

RMPs, produced by the DIII-D I-coil configured for strongly resonant  $n = 3$  operations, have been used to achieve stationary ELM-free H-modes at ITER-relevant collisionalities. During the

ELM-free phase of these discharges the density and radiated power remain stationary for long periods of time (up to 2,550 ms or about 17 energy confinement times). Comparisons with P-B mode stability theory indicate that the ELMs are eliminated by an RMP-induced reduction in the pedestal pressure gradient. The reduced pedestal pressure is brought about by a reduction in the pedestal particle content rather than an increase in the pedestal thermal diffusivity. We find that stochastic diffusion theory over estimates the electron thermal transport determined from the experimental data. In addition, unambiguous signatures of a resonant behaviour in the perturbing magnetic field are observed in the experiments, whereas estimates of resonant magnetic field shielding factors, due to the flow of a rotating plasma through a static perturbing field, suggest that strong magnetic field resonances should not occur and that a stochastic layer should not form. Thus, the experimental results are both surprising and theoretically challenging because they indicate that stochastic transport theory and rotational shielding theory are incomplete when applied to highly rotating collisionless pedestal plasmas. In addition, these experiments indicate that externally applied  $n = 3$  resonant magnetic perturbations may be a promising option for controlling ELMs and pedestal transport in future tokamak fusion plasmas.

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## Competing financial interests

The authors declare that they have no competing financial interests.

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