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Edge Localized Mode Control in DIII-D Using Magnetic Perturbation-Induced Pedestal Transport Changes*


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Abstract. Edge localized mode (ELM) control is a critical issue for ITER because the impulsive power loading from ELMs is predicted to limit the divertor lifetime to only a few hundred full-length pulses. Consequently, a technique that replaces the ELM-induced transport with more continuous transport while preserving the H-mode pedestal height and core performance would significantly improve the viability of ITER. One approach is to use edge resonant magnetic perturbations (RMPs) to enhance pedestal transport enough to reduce the pedestal pressure gradient $\nabla p_{ped}$ below the stability limit for Type I ELMs. In DIII-D, $n = 3$ RMPs have been used to eliminate Type I ELMs when the edge safety factor is in the resonant window $q_{95} \approx 3.5$ without degrading confinement in H-modes with ITER-relevant pedestal collisionalities $\nu_e^* \approx 0.2$. The RMP reduces $\nabla p_{ped}$ as expected, with $\nabla p_{ped}$ controlled by the RMP amplitude. Linear peeling-ballooning (P-B) stability analysis indicates that the ELMs are suppressed by reducing $\nabla p_{ped}$ below the P-B stability limit. The $\nabla p_{ped}$ reduction results primarily from an increase in particle transport, not electron thermal transport. This result is inconsistent with estimates based on quasi-linear stochastic diffusion theory based on the vacuum field (no screening of the RMP). The particle transport increase is accompanied by changes in toroidal rotation, radial electric field, and density fluctuation level $\tilde{n}$ in the pedestal, suggesting increased fluctuation-driven particle transport.

1. Introduction

Operation of next-step burning plasma devices with high fusion power gain $Q_{fus}$ requires operation at high pedestal pressures that lead to repetitive MHD instabilities known as edge localized modes (ELMs). In ITER, for example, achieving the target $Q_{fus} = 10$ is predicted to produce Type I ELMs with energy losses that exceed the ablation temperature for graphite.
and limit the divertor lifetime [2]. Consequently, a technique that replaces the impulsive 
ELM-induced transport with more continuous transport while preserving the H-mode 
pedestal height and core performance would significantly improve the viability of ITER. 
Several approaches to controlling the impulsive power loading due to ELMs are being 
studied, including: ELM-free H-modes (QH mode [3]), small ELM regimes [4], and H-
modes with pellet-triggered ELMs [5]. Another approach is to use edge resonant magnetic 
perturbations (RMPs) to enhance transport in the pedestal enough to reduce the pedestal 
pressure gradient $\nabla p_{\text{ped}}$ below the stability limit for Type I ELMs. In DIII-D, RMPs with 
toroidal mode number $n = 3$ have been used to eliminate Type I ELMs when the edge safety 
factor is in the resonant window $q_{95} \sim 3.5$ without significantly degrading confinement in H-
modes with ITER-relevant pedestal collisionalities $v_e^* \sim 0.2$ in both low [6-8] and high 
triangularity $\delta$ shapes.

In this paper, we present the results of ELM suppression experiments using an edge RMP in 
ELMy H-modes with ITER-relevant $v_e^*$. It is found that the RMP reduces $\nabla p_{\text{ped}}$, as expected [6], with the $\nabla p_{\text{ped}}$ decrease controlled by the RMP amplitude. Linear peeling-ballooning (P-
B) stability calculations using the ELITE code [9] indicate that the $\nabla p_{\text{ped}}$ reduction stabilizes 
the P-B modes associated with Type I ELMs [6-8]. The $\nabla p_{\text{ped}}$ reduction is primarily due to 
reduction of the pedestal density $n_e$, not the pedestal electron temperature $T_e$ [7,8]. This result 
is inconsistent with expectations from quasi-linear theory using the applied RMP (no 
screening) [7] and with simulations of the thermal transport in the stochastic layer using the 
fluid Monte Carlo heat transport code E3D with the applied RMP [10]. The pedestal toroidal 
rotation $\psi$ increases significantly during ELM suppression. At the same time, the H-mode $E_r$ 
well narrows and steepens. ELM suppression is also accompanied by an increase in density 
fluctuations $\tilde{\eta}$ due to core modes and broadband turbulence in the pedestal. The $E_r$ and $\tilde{\eta}$ 
changes suggest increases in particle transport due to convective cells or turbulent transport.

2. RMP approach to ELM suppression

The RMP ELM suppression concept [11] uses an edge RMP $\delta\psi_r^{m,n}$ which produces islands on 
rational surfaces in the pedestal. For large enough $\delta\psi_r^{m,n}$ these islands overlap, producing a 
stochastic layer in the magnetic field. Radial transport is enhanced in this stochastic layer, 
leading to a reduction in the edge $p_{\text{ped}}$ and $\nabla p_{\text{ped}}$ [Fig. 1(a)]. This $\nabla p_{\text{ped}}$ reduction moves the 
pedestal into the stable portion of the P-B stability diagram, as indicated by the green arrow 
in Fig. 1(b). Several features of H-mode pedestals facilitate RMP ELM suppression by 
localizing the perturbation to the pedestal: 1) the high magnetic shear which leads to closely 
spaced rational surfaces in the pedestal, so that less $\delta\psi_r^{m,n}$ is needed to generate the stochastic 
layer [11]; 2) the plasma rotation drop across the pedestal, weakening rotational screening of 
the RMP [12,13]; 3) the plasma pressure drop across the pedestal, weakening the pressure 
screening of the RMP [14]; and 4) the plasma collisionality increase across the pedestal, 
reducing the RMP screening and enhancing the transport [15].

In DIII-D, the RMP is provided by a flexible set of coils inside the vacuum vessel (the “I-
coil”), consisting of 2 sets of 6 single-turn window-frame coils, mounted above and below 
the outboard midplane. For these experiments, the I-coil was operated with a toroidal mode 
number $n = 3$ and strong edge resonant poloidal harmonics $6 < m < 13$ [Fig. 2(a)] that 
produce weakly overlapping vacuum field islands and a broad stochastic layer with remnant 
islands in the absence of screening by rotation or pressure [Fig. 2(b)].
Pedestal collisionality $\nu_e^*$ is an important parameter in these experiments because the fraction $\Delta W_{ELM}/W_{PED}$ of the pedestal stored energy $W_{PED}$ lost in an ELM $\Delta W_{ELM}$ increases as $\nu_e^*$ decreases, reaching 20% at ITER-relevant $\nu_e^*$ [1]. In addition, $\nu_e^*$ is predicted to impact both the penetration of the perturbation $\partial \theta_{r,m,n}^{BR}$ [15] and the stochastic layer transport rates. Consequently, performing the RMP ELM control experiments at ITER-relevant pedestal $\nu_e^*$ is important. In DIII-D, ITER-like values of pedestal $\nu_e^*$ based on generalization of the Sauter formula [16] for $Z_{eff} > 1$ [17] are achieved by pumping the DIII-D divertor. In the initial $\nu_e^* \sim 0.2$ RMP ELM suppression experiments, divertor pumping required operation at much lower triangularity $\delta = 0.37$ than that planned for ITER [Fig. 3(a)]. With completion of the Long Torus Opening Activity in early 2006, divertor pumping became possible with $\delta \sim 0.7$ ITER similar shapes (ISS) [Fig. 3(b)].
Fig. 3. Plasma shapes for the RMP ELM suppression experiments at $v_e^* \sim 0.2$ with (a) low $\delta$ and (b) high $\delta$ in an ITER-similar shape (ISS). (c) ELM suppression at $v_e^* \sim 0.2$ for the $\delta \sim 0.37$ (black) and $\delta \sim 0.7$ (red) shapes, showing, top to bottom: lower divertor recycling, I-coil current, pedestal toroidal rotation $v_\phi$, and H-mode confinement quality factor $H_{98y2}$.

3. Characterization of the ELM-suppressed state

Large ELMs have been completely eliminated in ELMing H-modes with $v_e^* \sim 0.2$ for both $\delta \sim 0.37$ (black) and $\delta \sim 0.7$ (red), as shown in Fig. 4. In each shape, the ELMing H-mode is replaced by a quiescent, steady-state RMP-assisted ELM-free H-mode with confinement quality factor $H_{98y2} \approx 1$. For $\delta \sim 0.7$, the discharge is switched from 100% co-plasma current neutral beam injection (co-NBI) to 18% counter-NBI at 4000 ms, producing a drop in pedestal toroidal rotation $v_\phi$ followed by a return to ELMing H-mode at 4105 ms. For each $\delta$, the pedestal $v_\phi$ increases when the ELMs cease. This pedestal spin-up is a feature of ELM suppression discharges that lack core MHD and maintain high performance, particularly at high $\delta$. The I-coil current needed to suppress ELMs increases at high $\delta$, in part because the rational surfaces are further from the I-coils (Fig. 3). The I-coil currents of 3 kA ($\delta \sim 0.37$) and 4 kA ($\delta \sim 0.7$) in Fig. 3 correspond to an increase in the $\delta_b^{11,3}$ Fourier amplitude of about 20%, and are representative of the increased current needed to stabilize ELMs at high $\delta$.

Application of 2 kA of I-coil current significantly reduces $\nabla p_{\text{ped}}$ as shown in Fig. 4(a). This reduction in the peak and width of $\nabla p_{\text{ped}}^{\text{TOT}}$ is accompanied by a shift in the radius of the peak, which is also important for P-B stability. Increasing the I-coil current to 3 kA narrows $\nabla p_{\text{ped}}^{\text{TOT}}$ further, and shifts the radius of the peak gradient further out. The $\nabla p_{\text{ped}}^{\text{TOT}}$ is roughly twice $\nabla p_{\text{ped}}^e$, indicating that the electron and ion channels share nearly equally in the $\nabla p_{\text{ped}}$ reduction [Fig. 4(a),(b)]. The $\nabla p_{\text{ped}}$ modifications in Fig. 4(a) result primarily from changes in the pedestal $n_e$ profile, not the $T_e$ profile, as shown in Fig. 4(c). This $n_e$ drop results from a substantial density pumpout when the RMP is applied, as has been reported in previous stochastic boundary experiments [18,19]. As the density pumps out, the ion and electron channels decouple, leading to a significant increase in $T_i$. 


4. Peeling-balooning stability analysis of RMP-assisted ELM-free H-modes

In experiments at $v_e^* \sim 0.2$, it is found that, within experimental uncertainties, the RMP ELM-free discharges are stable to P-B modes, whereas ELMing discharges become unstable to P-B modes just before an ELM occurs [6-8]. Profile data similar to that shown in Fig. 4 are used in a 1D stability code (ELITE [9]) to evaluate the P-B stability for an extensive set of ELMing and RMP-assisted ELM-free discharges. The stability calculations are based on accurate global reconstructions of full plasma profiles along with a broad range of mode numbers ($n = 5–30$).

The non-local stability results are represented in a simplified manner in Fig. 5. Here, the global experimental profiles are characterized by representative local values. Fig. 5 shows the normalized P-B mode growth rates $\gamma_N = \gamma / 0.5 \omega_e$ for 6 ELMing cases (magenta diamonds) just before an ELM and 14 RMP-induced ELM-free (green ellipses) cases. $\gamma_N$ is plotted as a function of the maximum value of the normalized pedestal pressure gradient $\alpha = -\mu_0 / (8 \pi^2 V) \partial V / \partial \psi (V^2 2\pi R_0) \partial p / \partial \psi$ (where $V$ is the plasma volume, $p$ 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 $j_{ped}^N$, 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 $j_{ped}^N = 0.53$. The color bar shows the value of $\gamma_N$ for the color contours in the plot.
that in RMP-assisted ELM-free discharges (green ellipses) the normalized growth rate lies inside the stable region when the error bars on the data are taken into consideration. On the other hand, ELMing discharges (magenta diamonds) consistently reside outside the stability boundary. Fig. 5 also shows that by increasing the I-coil current, the RMP-assisted ELM-free discharges can be made deeply stable (red I-coil current labels), and that ELMing discharges become unstable to P-B modes before ELMs are observed.

5. RMP-induced pedestal transport changes

Pellet perturbation experiments have been used to investigate the particle balance changes due to the I-coil (Fig. 6). Identical pellets were injected into three $\delta \sim 0.7$ discharges with similar recycling: (blue) ELMing H-mode (I-coil = 0 kA; 100% co-NBI), (red) RMP-assisted ELM-free H-mode (I-coil = 4 kA; 100% co-NBI), and (black) RMP-assisted ELM-free H-mode (I-coil = 4 kA; 20% counter-NBI). The density perturbation $\Delta n_e$ decayed twice as fast in the RMP-assisted ELM-free H-modes as in the ELMing H-mode, suggesting that at least part of the change in mean ion residence time $\tau_p^*$ is due to increased particle transport.

The small $T_e$ profile changes are unexpected from quasi-linear theory [8,19,20]. For $0.85 < \psi_n < 0.98$, the $T_e$ profile flattens and 1D power balance estimates indicate that $\chi_e^{\exp} = q_e/n_e V T_e$, where $q_e$ is the heat flux in the electron channel, increases to 2.8 m$^2$s$^{-1}$ for the 3 kA case in Fig. 4. For $0.985 < \psi_n < 1$, the $T_e$ profile steepens and the 1D power balance estimate is $\chi_e^{\exp} = 0.1$ m$^2$s$^{-1}$. Comparing these experimental estimates with the quasi-linear estimate of $\chi_{m,n}^{q_1} = v_{Te} D_{m,n}^{q_1} = 49$ m$^2$s$^{-1}$, where $v_{Te}$ is the electron thermal speed and $D_{m,n}^{q_1} = \pi R_o q_m \sum_{n=3}^{n=13} q_{m,n} (\partial \phi_m / B_T)^2 (m) = 3.5 \times 10^{-6}$ m is the magnetic field diffusivity [7,8], yields $\chi_{m,n}^{q_1}/\chi_e^{\exp} \sim 18$ at the top of the pedestal, which is a modest difference given the uncertainties in the estimate, while in the steep gradient region ($\psi_n > 0.985$), $\chi_{m,n}^{q_1}/\chi_e^{\exp} \sim 500$. This result is difficult to explain with quasi-linear theory, especially because in this region, screening of the RMP is predicted to be small [15].

Applicability of quasi-linear theory to these discharges is limited by the relatively weak stochasticity and the presence of multiple remnant islands [Fig. 2(b)]. To address this limitation, the magnetic field model from the TRIP3D code [11] has been used in the fluid heat transport code E3D [10,21] to simulate heat transport in the weakly stochastic magnetic field. Preliminary results indicate that the electron heat transport estimated using the vacuum field exceeds that measured in the experiment by a significant amount [10]. This discrepancy may arise from one of three limitations in the modeling: 1) use of the full vacuum RMP, 2) breakdown of the fluid model in this $v_{Te}^* \sim 0.2$ regime, and/or 3) lack of self-consistent $n_e$ profile evolution, and consequently of the ion-electron energy exchange in the pedestal [10].

5. Evidence for penetration of the RMP:
The discrepancy between theoretical and experimental power balance estimates of the electron thermal transport emphasizes the need to understand $\delta b_{r,m,n}$ inside the plasma. Several measurements indicate that the RMP penetrates the pedestal plasma some amount, including the existence of a narrow resonance in q-value for the ELM suppression. Langmuir probe measurements near the divertor strike point also show an increase in $T_e$ and a large drop in floating potential to -150 V, indicating the presence of hot electrons in the divertor during the RMP [22]. Simultaneously, the plasma potential at the main chamber wall becomes several hundred volts positive. These measurements are consistent with the connection of magnetic field lines from within the H-mode pedestal to the divertor target plates, leading to a flux of hot electrons (not thermalized in the SOL) to the targets and increased cross-field ion flux to the main chamber wall to maintain overall charge neutrality.

Further evidence for RMP penetration comes from comparison of the measured splitting of the divertor strike point with predictions of the intersection of homoclinic tangles with the target plates. The RMP splits the separatrix into stable and unstable manifolds which oscillate with increasing amplitude near the divertor X-point, forming “homoclinic tangles” [23]. These manifolds have been calculated using TRIP3D, and have been shown to govern the $T_e$ profile with E3D [10]. The predicted $T_e$ structures are seen in carbon line emission from the X-point region during RMP-assisted ELM-free H-modes [10,24]. The intersection of the tangles with the divertor target plates produces a spiral pattern on the target plates that has been calculated with TRIP3D and compared to measurements in RMP-assisted ELM-free H-modes at $v_e^* \sim 1$ [25]. The observed splitting at $v_e^* \sim 1$ exceeds the predicted splitting by 3, implying amplification of the vacuum $\delta b_{r,m,n}$. Preliminary comparisons of the predicted and observed splitting in RMP-assisted ELM-free H-modes at $v_e^* \sim 0.2$ suggest that there is no amplification or screening near the separatrix, consistent with expectations from Parail’s analytical screening model [13].

6. **Mechanisms for increased pedestal particle transport**

ELM suppression in $v_e^* \sim 0.2$ discharges is accompanied by changes to $v_\psi$, $E_r$ and density fluctuations $\tilde{n}$ in the core and pedestal. The $v_\psi$ increase occurs across the pedestal and SOL on a 50 ms timescale [Fig. 7(a)], but is largest near the separatrix where $v_\psi \approx 0$ in $v_e^* \sim 0.2$ discharges at $\delta \sim 0.37$. This minimum in $v_\psi$ becomes a well (counter-$I_p$ rotation, $v_\psi < 0$) at higher $\delta \sim 0.7$. On the same timescale as the pedestal $v_\psi$ increase, the H-mode $E_r$ well narrows as $E_r$ increases both inboard and outboard of the $E_r$ minimum [Fig. 7(b)]. This change increases $E_r$ shear outside of $\psi_n \approx 0.9$, but reduces $E_r$ shear for $\psi_n < 0.9$. There is an increase in $\tilde{n}$ for poloidal wavenumbers $k_\theta = 1 \pm 1$ cm$^{-1}$ during ELM suppression [Fig. 7(d)] as measured by FIR coherent scattering. This increase results from significant “washboard” activity from core modes, as well as an increase in the broadband $\tilde{n}$ level [Fig. 7(c)], although these changes are not spatially localized by this measurement. In the pedestal, $\tilde{n}$ measurements with homodyne reflectometry also show a change in both the character of the fluctuations [Fig. 7(e)] and in the overall amplitude [Fig. 7(f)]. These $E_r$ and $\tilde{n}$ changes suggest that the changes in particle balance result from increased particle convection due to either ion scale drift wave turbulence or convective cells.

7. **Conclusions**

An $n = 3$ edge RMP has been used in DIII-D to to eliminate Type I ELMs when the edge safety factor is in the resonant window $q_{95} \sim 3.5$ without significantly degrading confinement in H-modes with ITER-relevant pedestal $v_e^* \sim 0.2$. The RMP reduces $\nabla P_{ped}$
below the P-B stability for Type I ELMs. The $\nabla p_{\text{ped}}$ reduction is primarily due to reduction of $n_e$, not $T_e$. This result is inconsistent with expectations from quasi-linear theory using the applied RMP (no screening) and with simulations of the heat transport in the stochastic layer using the fluid Monte Carlo heat transport code E3D with the applied RMP. The pedestal toroidal rotation $v_\phi$ increases significantly during ELM suppression. At the same time, the H-mode $E_r$ well narrows and steepens, and density fluctuations increase due to core modes and broadband turbulence in the pedestal. The $E_r$ and $\tilde{n}$ changes suggest that the particle transport increases due to convective cells and/or turbulent transport.

Fig. 7. Pedestal (a) $v_\phi$ and (b) $E_r$ profiles during the ELMing phase before the I-coil and at two times during the RMP-assisted ELM-free H-mode for discharge 123301 with $v_\phi^* \sim 0.2$ and $\delta \sim 0.37$. (c) Color contour plot of the $\tilde{n}$ amplitude spectrum and (d) rms amplitudes for frequencies (blue) below and (red) above the 2 MHz carrier versus time for $k_\theta = 1 \pm 1$ cm$^{-1}$ (FIR scattering). (e) Color contour plot of the $\tilde{n}$ amplitude spectrum and (f) rms amplitudes for (blue) 10–400 kHz and (red) 13–100 kHz for a channel reflecting at $n_e = 1.3 \times 10^{13}$ cm$^{-3}$ ($\psi_n = 0.98$) in the pedestal.

References

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