Wide $q_{95}$ Windows of Edge-Localized-Mode Suppression by Resonant Magnetic Perturbations in the DIII-D Tokamak

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Edge-Localized-Mode (ELM) suppression by resonant magnetic perturbations (RMPs) generally occurs over very narrow ranges in the plasma magnetic safety factor $q_{95}$; however wide $q_{95}$ windows of ELM suppression are essential for operational flexibility in ITER and future reactors. Nonlinear two-fluid MHD simulations of DIII-D low-collisionality ITER-like plasmas reveal new understanding of the conditions required to access wide $q_{95}$ windows of ELM suppression relevant to the ITER high power mission. When the applied RMP of a given toroidal mode number $n$ is close to the threshold for resonant field penetration at the pedestal top, isolated magnetic islands can form, producing narrow $q_{95}$ windows of ELM suppression ($q_{95} \sim m/n$ and $\Delta q_{95} \sim 0.1$). However, as the threshold for field penetration decreases, by decreasing the plasma density, then multiple magnetic islands can penetrate at the pedestal top, giving rise to overlapping $q_{95}$ windows of ELM suppression, up to $\Delta q_{95} \sim 0.7$ seen in DIII-D. Nonlinear MHD simulations are in quantitative agreement with experiment and predict improved access to wide windows of ELM suppression at higher toroidal mode number with reduced impact on the pedestal pressure.

The power load onto plasma-facing components caused by type-I edge-localized modes (ELMs) [1] is a critical issue for the lifetime of in-vessel components in fusion reactors such as ITER [2]. Accordingly, significant effort has been invested on the control of ELMs [3,4], and one method to suppress ELMs is with the use of edge resonant magnetic perturbations (RMPs) [5-15]. One common characteristic of ELM suppression by RMPs is the existence of well-separated narrow $q_{95}$ windows ($\Delta q_{95} \sim 0.1$) of ELM suppression [6,15-20], where $q_{95}$ is the magnetic safety factor at 95% of the normalized poloidal magnetic flux. However, wide $q_{95}$ windows of ELM suppression are highly desirable for operational flexibility in ITER and future reactors. Evidence for expanded windows of ELM suppression have been observed [21], however, to date, no empirical or predictive understanding exists for explaining the cause of these wide windows of ELM suppression and how they may be achieved in future reactors such as ITER.

In this Letter we demonstrate predictive understanding of the requirements for wide $q_{95}$ windows of ELM suppression (up to $\Delta q_{95} \sim 0.7$) in low-collisionality DIII-D ITER-shape plasmas based on nonlinear two-fluid MHD simulations. We find that for an $n = 3$ RMP amplitude near the threshold of resonant field penetration, only isolated narrow magnetic islands are driven at the pedestal top [22], producing narrow $q_{95}$ windows of ELM suppression. However, for similar RMP amplitude, as the density is reduced (and/or the plasma rotation is increased in the direction of the plasma current), the threshold for field penetration decreases, giving rise to multiple magnetic islands and wider $q_{95}$ windows of ELM suppression. Nonlinear two-fluid MHD simulations reproduce observations in DIII-D and predict that an increase in the toroidal mode number of the RMP will result in wider $q_{95}$ windows of ELM suppression with less impact on the pedestal pressure for similar RMP amplitude. This result has important implications for the operation of the ITER ELM control coils and for the optimization of ELM suppression in existing experiments.

In DIII-D, RMPs for ELM suppression are produced by in-vessel coils (called I-coils [23]). For our study, the upper and lower row of I-coils are configured in even parity (same sign of current in upper and lower coils), with toroidal mode number $n = 3$ [23]. These discharges are in the ITER Similar Shape (ISS) with low pedestal collisionality ($\nu_e \approx 0.05-0.2$). The plasma current is increased slowly over ~ 2 s to produce a downward scan in $q_{95}$ in plasmas with the following parameters: toroidal field $B_T = 1.9$ T, normalized beta $\beta_n \sim 1.8-2.2$, pedestal density $n_{e,ped} \approx 1.5-4 \times 10^{20}$ m$^{-3}$, triangularity $\delta \sim 0.5$, co-$I_p$ neutral beam power 6-8.5 MW with similar injected torque 5-7.5 Nm.

![Fig. 1](image-url)

Fig. 1. The evolution of (a-c) log of $\Delta n_e$ and $n = 3$ I-coil current for three plasmas vs $q_{95}$, (d) pedestal electron pressure $P_{e,ped}$, and (e) pedestal electron density $n_{e,ped}$ for #145380 (blue curves), #132741 (red curves) and #157303 (black curves). The windows of ELM suppression are shaded in yellow.

In DIII-D we observe that for plasmas with similar $n = 3$ RMP amplitude, beam power and torque, as the plasma density decreases the $q_{95}$ windows of ELM suppression expand and eventually merge to create wide windows of ELM suppression. The discharges in Fig. 1 show the expansion and merging of $q_{95}$ windows of ELM
suppression (Fig. 1a-c) as the plasma density (Fig. 1e) is lowered in similar discharge conditions.

It has been shown elsewhere that the pedestal density and plasma flow frequency $\omega_n = E_r/|\mathbf{R}B_0|$ play a key role in determining the RMP amplitude for the penetration of resonant magnetic fields at the top of the pedestal [22, 24] in the DIII-D tokamak. As the pedestal density decreases, the threshold RMP amplitude $\delta B/\mathbf{B}$ for resonant field penetration also decreases. In this Letter we show that the decrease in the pedestal density for nominally similar plasmas lead to the expansion and overlap of the $q_{95}$ windows of ELM suppression in DIII-D. We further show that these windows of ELM suppression are in quantitative agreement with nonlinear MHD simulations for the penetration of resonant fields near the pedestal top.

Three discharges with different pedestal density and ELM suppression window are shown in Fig. 1 for similar discharge conditions and $n = 3$ RMP amplitude. At the highest pedestal density $n_{ped} \sim 3.5 \times 10^{19}$ m$^{-3}$ ($\#145380$, Fig. 1a), ELMs are suppressed in two separate $q_{95}$ windows, $3.46 < q_{95} < 3.57$ and $3.18 < q_{95} < 3.31$ and a sparse window of ELMs is observed for $3.8 < q_{95} < 3.85$. These ELM suppression windows occur for $q_{95} \approx 11/3$, $10/3$ and $9/3$, as highlighted in previous studies [20]. By lowering the $n_{ped}$ to $2.5 \times 10^{19}$ m$^{-3}$ ($\#132741$, Fig. 1b), the two main ELM suppression windows merge $3.18 < q_{95} < 3.6$ and the sparse window of ELMs is now fully suppressed, $3.73 < q_{95} < 3.9$. For the lowest pedestal density $n_{ped} \sim 1.5 \times 10^{19}$ m$^{-3}$ ($\#157303$, Fig. 1c), only a single wide window of ELM suppression is observed for $3 < q_{95} < 3.75$. Isolated ELMs are observed, three of which are triggered by sawteeth, but regular ELMing activity is eliminated. For all these discharges the $E \times B$ frequency $\omega_b (= \pm 10 \pm 2$ krad/s) and the diamagnetic drift frequency $\omega_d (= \pm 30 \pm 5$ krad/s) at the pedestal top do not vary significantly with density. These three discharges are representative of a set of 50 discharges that demonstrate the trend of expanding windows of ELM suppression with decreasing density.

Given the success of the TM1 model in predicting the density threshold for ELM suppression and the origin of density pump-out in DIII-D [22], we apply the same model to understand and predict the requirements for wide $q_{95}$ windows of ELM suppression. TM1 is a nonlinear two-fluid model in cylindrical geometry [25,26], and includes the effects of diamagnetic drift and ion polarization current, which are important in describing resonant field penetration and transport in the pedestal region. The $n = 3$ RMP boundary condition for TM1 comes from full toroidal geometry ideal MHD plasma response calculations using the GPEC code [27].

In the following simulations, experimental profiles are used from Thomson scattering measurements and charge exchange recombination spectroscopy. The kinetic equilibrium is generated from TRANSPI [28] and EFIT [29]. Transport coefficients are obtained from TRANSPI power and particle balance calculations, which are $D_n \approx \phi \approx \chi \approx 1$ m$^2$/s at the top of pedestal for all the discharges in Fig. 1. The temperature dependent neoclassical resistivity [30] is used, which ranges from $0.8 \times 10^{-7} - 1.5 \times 10^{-7}$ $\Omega$m at the pedestal top for the same discharges.

We first show that the narrow $q_{95}$ windows of ELM suppression in the high-density discharge $\#145380$ are reproduced by TM1. Fig. 2b shows the TM1 prediction of the pedestal electron pressure $P_{ped}$ due to the penetration of the $m/n = 10/3$ magnetic island for a sequence of $q$-profiles with different $q_{95}$ values as shown in Fig. 2a from times $t_1$ to $t_5$. We use the GPEC calculated total RMP strength ($\sim 7.8$ G) for the $m/n = 10/3$ field at $q_{95} = 1$ for TM1. The TM1 simulations show that resonant field penetration occurs at the $q = 10/3$ surface near the pedestal top for times $t_1$ to $t_5$. Screening of the resonant field occurs at $t_5$ when the rational surface moves too far into the gradient region of the pedestal. The $m/n = 10/3$ island (width $\Delta q_{95} \approx 0.016$) at the top of the pedestal is very narrow, but produces a significant $\approx 15\%$ reduction in the electron pedestal pressure according to TM1. Good agreement is shown between the measured pressure profiles (dotted curves) and TM1 simulations (solid curves) for times $t_1$ and $t_5$ in Fig. 2b.

We note that the largest pressure reduction occurs at times $t_1$ and $t_5$, while almost no pressure reduction occurs at $t_1$. The deeper the island penetrates into the gradient region of the pedestal the greater the pressure (and width [24]) reduction of the pedestal. However, if the rational surface is pushed too far into the gradient region then the island is screened and we see no pressure reduction at $t_5$. The $m/n = 10/3$ penetration threshold and pedestal pressure reduction from TM1 simulations versus $q_{95}$ and RMP amplitude are shown in Fig. 2c,d, respectively. A pedestal pressure reduction of $\approx 15\%$ ($\Delta P_{ped} = -0.6$ kPa) is indicated by the blue contour in Fig. 2d and a similar fractional reduction in the pedestal width is observed in Fig. 2b. These simulations are consistent with heuristic arguments originally proposed for how magnetic islands could stabilize ELMs by preventing the expansion of the pedestal to an unstable width [20].

Additional TM1 simulations using all resonant RMP harmonics $m/n = 9/3$, $10/3$, $11/3$ and $12/3$ for $\#145380$, identifies all the ELM suppression windows in experiment and even the sparse ELM window at higher $q_{95}$, as shown in Fig. 3a. The EPED model [20] is used to predict the pedestal pressure threshold for PBM onset (black), with the experiment in blue and TM1 simulation in red. Fig. 3b shows the contour of pedestal pressure reduction versus $q_{95}$ and RMP strength. The RMP amplitude for the $12/3, 11/3$, $10/3$ and $9/3$ components are very similar ($B_r \approx 7.8$ Gauss,
horizontal dashed line in Fig. 3b) at $\psi_B = 1$ based on GPEC analysis. From Fig. 3a, the TM1 simulations closely match the observed $q_{95}$ width and magnitude of the pedestal pressure reduction for all of the ELM suppression windows. This agreement demonstrates that the pedestal pressure reduction well below the EPED prediction is consistent with the pedestal stabilizing effects of narrow magnetic islands. We also note that the RMP amplitude at $\psi_B = 1$ required to affect a 15% reduction in the pedestal pressure (blue curve in Fig. 3b) decreases as the poloidal mode number decreases due to the $r^m$ dependence of the field strength with radius [31]. This explains why lower $q_{95}$ values (lower $m$) tend to have more robust and wider ELM suppression windows in DIII-D.

Fig. 3. (a, c) Comparison of pedestal pressure between experiment (blue), EPED prediction (black) and TM1 simulation (red). (b, d) TM1 simulated pedestal pressure change $\Delta P_{ped}$ versus resonant field strength $B_0(G)$ and $q_{95}$. (a, b) #145380 is the high density case $n_{e,ped} \approx 3.5 \times 10^{19}$ m$^{-3}$ and (c, d) #132741 is for the lower density case $n_{e,ped} \approx 2.5 \times 10^{19}$ m$^{-3}$. The blue curve corresponds to a 15% reduction in the pedestal pressure, and the blue curve in Fig. 3b is overlaid in Fig. 3d by blue dotted curve to show the change in the width of $q_{95}$ window with density decrease.

Fig. 3c,d presents TM1 simulations for lower pedestal density discharge #132741, shown in Fig. 1b with $n_{e,ped} \approx 2.5 \times 10^{19}$ m$^{-3}$. The resonant field strength (horizontal dashed line in Fig. 3b,d) is similar to the higher density discharge based on GPEC calculations, and both the E×B frequency (~10 krad/s) and diamagnetic drift frequency (~30 krad/s) at the top of pedestal are similar. The main difference between the two discharges is that at lower density the threshold for field penetration decreases [24] for all $m$, which leads to the widening of the ELM suppression windows as shown in Fig. 3d. Note that in Fig. 3d we overlay the -15% blue contour from Fig. 3b (blue dashed curve) to show that as the threshold for penetration at the top of the pedestal decreases, then the width of the $q_{95}$ window of ELM suppression naturally increase for a similar RMP amplitude. Of note, the operation at lower density reveals a robust $m/n = 11/3$ ELM suppression window which had been marginal at higher density (from Fig. 3a,b). We also observe the near merging of the two previously separated ELM suppression windows for $m/n = 10/3$ and 9/3.

The predicted emergence of the $m/n = 11/3$ ELM suppression window at lower density is an important finding. The 11/3 suppression window has been marginal in DIII-D, however a connection had not been drawn till now between the marginality of the window and the pedestal density. From Fig. 3c, the pedestal pressure can be seen to oscillate with $q_{95}$, as predicted by TM1 due to the passage of the 10/3 and 9/3 magnetic islands across the pedestal top.

Next we address the lowest pedestal density $n_{e,ped} \approx 1.5 \times 10^{19}$ m$^{-3}$ discharge #157303, shown in Fig. 1c, which has the widest ELM suppression window. Fig. 4a shows the merging of all three windows of ELM suppression, indicated by the sustained low pedestal pressure versus $q_{95}$ in experiment (blue) and TM1 simulation (red). The pedestal pressure no longer oscillates with $q_{95}$ and stays well below the EPED prediction, due to the simultaneous appearance of multiple magnetic islands near the top of the pedestal, as shown in Fig. 4c. Fig. 4b shows the TM1 predicted reduction in the pedestal pressure versus $q_{95}$ using the GPEC calculated RMP strength (≈6.5 Gauss) at $\psi_B = 1$ for this discharge. The RMP strength shown by the horizontal dashed line in Fig. 4b now intersects multiple overlapping ELM suppression windows.

These ELM suppression windows now overlap at low density because the magnetic island at $q = 10/3$ is not fully screened before the adjacent island at $q = 9/3$ enters the top of the pedestal as $q_{95}$ decreases. This produces a continuous band of ELM suppression, $3 < q_{95} < 3.75$, limited only by the range of the $q_{95}$ scan. Fig. 4c shows the Poincaré plot of the magnetic flux surfaces overlaid with the TM1 pressure profile (white) and original pressure profile (blue) for (c) $q_{95} = 3.225$ and (d) $q_{95} = 3.15$, indicated by the white dots in Fig. 4b.

![Fig. 3](image3.png)

![Fig. 4](image4.png)
substantially compromise pedestal pressure in order to achieve robust ELM suppression, as this would significantly lower fusion power production. Fig. 4b,c shows an unacceptably large \( \approx 40\% \) reduction in the pedestal pressure with two \( n = 3 \) islands near the top of the pedestal. Therefore, we must seek methods for the suppression of ELMs over wide \( q_{ps} \) windows while minimizing the impact of the RMP on the pedestal pressure. We show in principle that this can be achieved by operating at higher toroidal mode number.

Here we show from TM1 simulations that by operating at higher toroidal mode number ELMs may be suppressed while avoiding the large reduction in the pedestal pressure. The key point is that if the radial separation of the magnetic islands can be reduced by increasing the toroidal mode number, then overlapping \( q_{ps} \) windows of ELM suppression may occur near the RMP threshold for ELM suppression, thereby minimizing the impact of the RMP on the pedestal pressure.

![Fig. 5. TM1 simulated pedestal pressure change \( \Delta P_{ped} \) versus resonant field strength \( B_r(G) \) and \( q_{ps} \) for \( n = 4 \) RMP based on equilibrium and profiles of \#145380. The blue line corresponds to a 15\% reduction in \( P_{ped} \).](image)

We test this hypothesis using the high density discharge \#145380 and apply an \( n = 4 \) RMP in TM1 with the same \( n = 3 \) RMP amplitude \( (B_r = 7.8 \text{ G}) \) used in Fig. 3a. Fig. 5 shows the TM1 prediction of the pedestal pressure reduction (contours) versus the \( n = 4 \) RMP strength and \( q_{ps} \). Multiple ELM suppression windows are predicted for each resonance from \( m/n = 16/4 \) to 12/4. The blue line in Fig. 5 corresponds to a 15\% reduction in the pedestal pressure. For the RMP amplitude of 7.8 Gauss at \( q_{ps} = 1 \), we predict the merger of the 12/4, 13/4 and 14/4 ELM suppression windows. This is in contrast to \( n = 3 \) RMPs where there are no overlapping ELM suppression windows even for much larger RMP amplitudes (Fig. 3b). Therefore the TM1 simulations predict that the closer proximity of adjacent rational surfaces at higher-\( n \) allows multiple islands to appear at the pedestal top near the RMP threshold for field penetration, producing wide \( q_{ps} \) windows of ELM suppression with weak pedestal pressure reduction. These results indicate that the proposed M-coils for DIII-D [32] may enable access to wide windows of ELM suppression while minimizing the pressure reduction at the pedestal top. By extension we also anticipate that operating ITER with dominant \( n = 4 \) RMPs could allow access to wider windows of ELM suppression relative to \( n = 3 \) operation. The currently planned ITER ELM control coils can in principal operate with dominant \( n = 4 \) RMP [5] but with some additional harmonics.

In this Letter we have demonstrated the conditions for accessing wide \( q_{ps} \) windows of RMP ELM suppression in low-collisionality DIII-D ITER shape plasmas. We have shown that nonlinear two-fluid MHD simulations agree quantitatively with experiment for the density dependence of \( q_{ps} \) windows of ELM suppression for \( n = 3 \) RMPs. These simulations show that wide windows of ELM suppression occur when multiple magnetic islands are driven near the top of the pedestal. We predict that RMP operation at higher toroidal mode number will enable access to wide windows of ELM suppression with weaker pedestal pressure reduction in low-collisionality DIII-D ITER-like plasmas.

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