Abstract:

Full ELM suppression with mixed \( n=2 \) and \( n=3 \) has been achieved in standard type-I ELMy H-mode operational window in both DIII-D and EAST. Mixed \( n=2 \) and \( n=3 \) toroidal harmonic RMP lower the threshold current for ELM suppression by a factor of 30% compared to the single \( n=3 \) RMP in DIII-D, considering the metric with perturbed magnetic energy in coil currents. Plasma response indicates that the \( n=2 \) field via rotation braking helps to penetrate the \( n=3 \) harmonic which eventually leads to ELM suppression. MHD simulation shows good agreement in both mode structure and phase with the observations during ELM mitigation, while it has a phase shift compared to the observed response during ELM suppression in DIII-D, which is similar to that in EAST. Experiments using mixed toroidal harmonic RMPs with static \( n=3 \) and rotating \( n=2 \) harmonics have validated predictions that divertor heat and particle flux can be dynamically controlled while maintaining ELM suppression in both DIII-D and EAST.

1 INTRODUCTION

The resonant magnetic perturbations (RMPs) produced by magnetic coils outside the plasma have been demonstrated to be a robust technique for edge localized mode (ELM) control in many tokamaks. Both DIII-D [1] and EAST [2] have demonstrated ELM suppression with RMP. Full ELM suppression has been achieved with a single toroidal mode number, either \( n = 3 \) [1] or \( n = 2 \) [3] in DIII-D in the past. ELM suppression using a reduced number of I-coils in DIII-D suggested possible contribution of mixed toroidal harmonic spectra [4]. This work motivated further investigation using mixed toroidal harmonic RMPs in DIII-D and EAST to explore its potential capability in ELM and divertor power load control. Here mixed toroidal harmonic RMPs are defined as a linear superposition of two or more harmonics of different toroidal mode numbers \( n \).

The 3D footprint on the divertor induced by RMP during ELM suppression may introduce toroidally localized hot spots on the divertor [5]. Therefore, it is necessary to vary the heat and particle flux patterns on the divertor target during the application of RMPs while maintaining ELM suppression [6]. Rotating RMP experiments demonstrated recently as a promising method [7–9] in controlling the steady state particle and heat flux on the divertor, when the transient power loads induced by ELMs have been eliminated by RMPs. It shows a possible way to use time-varying RMPs for the dynamic control of divertor heat and particle flux while maintaining ELM suppression. By varying the phase of one harmonic, the mixed toroidal harmonic RMPs may change the divertor power load distribution, while the ELM-suppression is maintained. This may require smaller variation in coil current over the rotating single \( n \) RMPs case, easing engineering limits on the coil lifetime.
Mixed toroidal harmonic RMPs are used on both EAST and DIII-D to reduce the threshold for ELM suppression and to spread the divertor heat flux. A detailed description of the in-vessel RMP coils in DIII-D can be found in Ref. [1] and that in EAST can be found in Ref. [10]. It is demonstrated in this experiment in DIII-D that mixed n=2 and 3 toroidal harmonic RMPs lower the threshold current and the resultant energy in the magnetic perturbations for ELM suppression compared to the single n RMP. To understand the ELM suppression mechanism, detailed comparison between the plasma response observed on magnetic sensors during ELM mitigation and suppression and that from the linear MHD modeling by MARS-F are carried out. Experiments using mixed toroidal harmonic RMPs with a static n=3 and a rotating n=2 RMPs in DIII-D and EAST validate predictions that divertor heat and particle flux can be dynamically controlled while maintaining ELM suppression.

2 MIXED N RMPs FOR ELM CONTROL IN DIII-D

Similar target plasmas with safety factor at the magnetic surface with 95% of the normalized poloidal flux $q_{95} \approx 3.4 - 3.7$, normalized beta $\beta_n \approx 1.8 - 2$, normalized density to Greenwald limit $\langle n_e \rangle / N_G \approx 0.4 - 0.6$, and single null standard type-I ELMy H-mode plasma was chosen for both DIII-D and EAST in this experiment.

2.1 Lower the threshold coil current for ELM suppression in DIII-D

Compared to the case with single n = 3 or n=2 RMP, mixed toroidal n = 2 and 3 harmonic RMPs lower the required coil current for ELM suppression. As shown in figure 1, in DIII-D shot 170077 (blue lines), even parity n = 3 currents are applied in the upper and lower coils and the amplitude is slowly increased in time. In the other shot 170079 (red lines) with the same target plasma, mixed toroidal n = 2 and 3 harmonic RMPs are slowly ramping up. Indicated by the vertical dashed lines, the ELM-suppression is achieved in shot 170077 when $I_{n=3} = 3.50 \text{kA}$ at about 4210 ms. In shot 170079, the ELM suppression is achieved earlier at 3700 ms, at which time the current of toroidal harmonic RMPs is $I_{n=2} = 0.87 \text{kA}$ and $I_{n=3} = 2.28 \text{kA}$. In both of these two shots, density pump out effect increases with increasing RMP current as shown in figure 1(d). ELMs cannot be suppressed by a pure n = 2 RMP with maximum coil current of 5 kA in the same target plasma in another discharge 170078 (not shown). Considering the power supply, the maximal total current of the coils at the threshold current for ELM suppression in the mixed-n case is $2.28 \text{kA} + 0.87 \text{kA} = 3.15 \text{kA}$, which is around 10% less than that in the pure n = 3 case 3.50 kA. Considering the requirement of perturbed magnetic energy which is proportional to the square of coil current, the equivalent current of total energy in the mixed-n case ( $\sqrt{2.28^2 + 0.87^2} \text{kA} = 2.44 \text{kA}$) is around 30% less than that in the pure n = 3 case. Therefore, the results in this experiment suggest that mixed toroidal harmonic RMP offers a better path to ELM control, because it allows us to apply less current to control ELMs, especially when the required current of single harmonic RMP is too high for available power supplies.

2.2 Nonlinear bifurcation in plasma response to access ELM suppression in DIII-D

Plasma response plays an important role during RMP application and is vital for understanding the physical mechanism for ELM control [11–15]. In recent years, non-linear plasma response during ELM suppression has been observed in DIII-D [3] and EAST [2]. To understand the mechanism of ELM suppression with mixed toroidal harmonic RMPs, a detailed study of plasma response in this experiment [16] is carried out in the following.
Plasma response measured by magnetic sensors indicates that the \( n = 2 \) field helps to penetrate the \( n = 3 \) mode which eventually leads to ELM suppression. As shown in Fig. 2 (a), ELMs are suppressed once the \( n = 2 \) RMP current (blue solid) exceeds a critical level in DIII-D discharge 170112, in which a constant static \( n = 3 \) RMP (blue dashed) is applied during these periods. Without the additional \( n=2 \) RMP, ELMs are only mitigated by the single \( n=3 \) RMP. It can be seen from the plasma response measured by the high field side (HFS) magnetic sensors in Fig. 2 (b) that the \( n = 3 \) plasma response (red) suddenly drops in every transition from ELM mitigation to suppression, which is consistent with the nonlinear bifurcation from ELM mitigation to suppression observed in EAST [2]. The \( n = 2 \) plasma response (blue) is mainly a linear response, because it is proportional to the \( n = 2 \) coil current and the amplitude of response agrees with the linear relation in figure 3. However, the jumps in the \( n = 3 \) plasma response are not consistent with the linear relation. These jumps indicate the penetration of \( n = 3 \) harmonic, and suggests that the small \( n = 2 \) perturbation may help this penetrate via rotation braking effect. Plasma rotation near the pedestal top increases slightly after ELM suppression is accessed in DIII-D shot 170112. This moves the position where electron perpendicular rotation equals zero outwards and towards the \( q = 3 \) rational surface. It may cause easier penetration of the \( n=3 \) harmonic. The penetration of \( n = 3 \) modes near the pedestal top eventually leads to ELM suppression. This might be the reason why ELM suppression by the mixed toroidal harmonic RMPs requires lower threshold current.

A linear dependence of the measured plasma response on the applied field is observed in the mitigation stage, while a non-linear jump of plasma response is observed during the transition from mitigation to suppression of ELM in DIII-D. In DIII-D discharge 170085 and 170086 with \( n = 2 \) and \( n = 3 \) RMP harmonics flipped separately, ELMs are first mitigated and then suppressed by the \( n=3 \) RMP and only ELM mitigation can be achieved by the \( n=2 \) RMP. As shown in figure 3, the plasma response on the HFS increases linearly with the RMP coil current, during ELM mitigation phases by \( n = 2 \) or \( n = 3 \). After accessing ELM suppression with \( n=3 \) RMP, the plasma response to \( n = 3 \) jumps away from the linear relation. This jump is a non-linear bifurcation which indicates a
mode structure change during the transition from ELM mitigation to suppression.

Fig. 4 shows the measured real part (a) and phase (b) of the n=3 response field (with symbols) by the HFS vertical array of magnetic sensors during ELM mitigation (blue) and suppression (red) in DIII-D discharge 170085, and the comparison with linear MHD simulation results (solid lines) using the MARS-F code [11]. It is shown that the modeling results in both phase and amplitude agree well with the observation during the mitigation period. However, the simulation results have a 90° difference in phase compared to the measurement during the ELM suppression period. This is similar to that observed in EAST [2]. This difference during ELM suppression phase indicates that there is still a limitation in the application of linear MHD modeling for the simulation of ELM suppression.

2.3 Dynamic control of flux to divertor during ELM suppression in DIII-D

ELM suppression over one full cycle of a rotating n=2 RMP combined with a static n=3 RMP field has been achieved in a low pedestal collisionality regime with $\nu_{\text{e,ped}} \approx 0.2$ in DIII-D. Fig. 5 (a) shows that the amplitudes of coil current harmonics are $I_{n=2} = 1.5$ kA (blue solid) and $I_{n=3} = 3$ kA (blue dotted) throughout the time period shown. The n = 3 harmonic is static, while the n = 2 is rotating (red line shows the phase) with a frequency of 1.5 Hz. Fig. 5 (b) shows that ELMs are suppressed during a full rotation of the $n = 2$ fields between 4 and 4.75 s. This result produced an opportunity to control the 3D heat flux on the divertor [17].

Strike point splitting in heat flux during the application of RMP is observed in low collisionality regime in DIII-D. As shown in green lines in Fig.6 (a), prominent heat flux splitting on the outer divertor has been observed using IR camera during ELM suppression by $n=3$ RMP in this low collisionality regime in DIII-D. It agrees well with modeling of field penetration depth, $1 - \rho_{\text{min}}$, shown in Fig.6 (b), using TOP2D [18] with plasma response modeled by MARS-F. Here $\rho_{\text{min}}$ is the radius of innermost magnetic surface in flux coordinates that the field line started form the divertor plate position with a major radius $R - R_x$ can reach, where $R = R_x$ is the major radius for the main strike point without RMP. The surface with $\rho = 1$ is the last closed flux surface and hence $\rho_{\text{min}} < 1$ means that the field line connects to the flux surface inside the last closed flux surface. The field line started from the position with higher $1 - \rho_{\text{min}}$ corresponds to a deeper connection to the hot plasma. Therefore, toroidally localized hot spots may form at the locations with peaks in the modeled $1 - \rho_{\text{min}}$. The positions of the two additional peaks induced by $n=3$ RMP in the observed heat flux (green line) agrees well with that of the peaks in the modeled $1 - \rho_{\text{min}}$ (green points).
Experiments using mixed toroidal harmonic RMPs, with a rotating \( n=2 \) toroidal harmonic combined with a stationary \( n=3 \) toroidal harmonic, have validated predictions that divertor heat and particle flux can be dynamically controlled while maintaining ELM suppression in DIII-D. Strong changes in the three-dimensional heat and particle flux footprint in the divertor measured by IR and visible cameras were observed after the application of an additional rotating \( n = 2 \) harmonic perturbations as shown in blue (0 degree phase of \( n = 2 \) RMP) and red (180 degree phase of \( n = 2 \) RMP) lines in Fig.6 (a). Variation of the heat flux splitting pattern at different \( n = 2 \) phases in these mixed toroidal harmonic cases is observed and consistent with the variations of \( 1 - \rho_{min} \) in the modeling shown in Fig.6 (b). A periodic change in the heat flux profile is found to keep pace with the \( n=2 \) harmonic rotation. This indicates that the change of the heat flux strength on a fixed point can be controlled with the rotation of the \( n=2 \) harmonic. The particle flux footprint on the divertor also shows a similar behavior as the heat flux one, and it’s pattern also agrees well with the modeling [17].

3 MIXED \( N \) RMPs FOR ELM CONTROL IN EAST

ELM suppression was previously achieved in EAST with \( n = 1 \) and 2 RMPs in a relatively high \( \theta_{95} \) (\( \geq 5 \)) and low beta (\( \beta_N \leq 1 \) ) [2]. It is extended recently to low \( \theta_{95} \) (\( \approx 3.2-3.7 \)) and higher beta (\( \beta_N \approx 1.8 - 2 \)) using higher \( n \) RMPs, which is similar to DIII-D shown in previous section. Here the auxiliary heating power in this experiment in EAST includes 2.5MW Neutral Beam Injection (NBI) and 1MW Lower Hybrid Current Drive (LHCD). The normalized pedestal electron collisionality is slightly higher, and is around \( \nu_{ped} \approx 0.5 - 0.8 \). The plasma rotation is around half of that in DIII-D. An upper single null plasmas is used in this experiment in EAST, where the upper divertor is made from tungsten. Full ELM suppression is achieved by all \( n = 2 - 4 \) RMPs in this operational window.

3.1 ELM suppression using mixed \( n \) RMPs in EAST

![FIG. 7: ELM suppression using mixed \( n = 2 \) and 3 RMPs in EAST pulse 79016. Temporal evolution of (a) particle flux on the divertor (black), \( n = 2 \) (blue solid) and 3 (red dashed) RMP current, (b) plasma density(blue), and the normalized plasma beta (red).](image1)

![FIG. 8: ELM suppression using mixture of rotating \( n = 2 \) and static \( n = 3 \) RMP in EAST pulse 79013. Temporal evolution of (a) \( n = 2 \) (blue solid) and 3 (red solid) RMP current and the \( n = 2 \) RMP phase (dashed line), (b) \( D_n \) (black), and plasma density(blue), and the normalized plasma beta (red).](image2)

Full ELM suppression is also achieved by using mixed \( n = 2 \) and 3 RMPs in this window. Figure 7 shows ELM suppression using RMPs with mixture of static \( n = 2 \) and \( n = 3 \) harmonics in EAST pulse 79016. The amplitudes of coil current for both \( n = 2 \) and 3 harmonics are 2.5 kA. The toroidal field strength \( B_T = 1.5 \) T, the plasma current \( I_p = 450 \) kA, and \( \theta_{95} \approx 3.7 \). Strong density pump-out effect is observed during the application of mixed toroidal harmonic RMP. It is shown that ELM suppression is achieved for about 1.5s. The energy confinement increase
slightly in this regime. The increase of stored energy is mainly contributed from the increase of ion temperature during the application of RMP, similar to the observations in DIII-D [19]. However, the particle confinement decreased also for the impurities after the application of RMP. Tungsten concentration is significantly reduced after the application of RMP.

3.2 Divertor flux control during ELM suppression in EAST

The achievement of ELM suppression using mixed toroidal harmonic RMP allows us to control divertor heat load dynamically by rotating the \( n = 2 \) harmonic, which is demonstrated in EAST pulse 79013. As shown in figure 8, a rotating \( n = 2 \) harmonic is applied in the upper coils, while the \( n = 3 \) harmonic keeps constant in the lower coils. The amplitude of both \( n = 2 \) and \( n = 3 \) harmonics are 2.5 kA, respectively. Strong density pump-out effect is also observed in this case. It can be found that ELMs are suppressed form 4.9 s to 5.5 s, which is about 60% of one rotating cycle. The \( \beta_N \) increases from 1.7 to 1.9 during ELM suppression suggesting an improvement of energy confinement.

Figure 9 shows the temporal evolution of the particle flux to the upper divertor measured by Langmuir probes at D-port (\( \phi = 80^\circ \)) and O-port (\( \phi = 327^\circ \)) during the application of RMP with mixed rotating \( n = 2 \) and static \( n = 3 \) RMPs. Footprint splitting has been observed clearly in the particle flux in both of the two arrays of probes. The 3D pattern of the particle flux to upper outer divertor shifted for two full toroidal cycles, keeping pace with the \( n = 2 \) harmonic rotation. An obvious phase shift between the two arrays can also be found in the figure. The shaded area denotes the time range of ELM suppression. During ELM suppression, the steady state particle flux at the secondary strike points moves effectively with the rotating \( n = 2 \) harmonic. This demonstrates the possibility of dynamic control of divertor heat load while maintaining ELM suppression in EAST.

It is interesting to notice that the 3D pattern induced by ELMs during ELM mitigation are locked to the phase of \( n = 2 \) RMP when we zoom in the time window and show it in Figure 9 (d). The location of the secondary strike points induced by ELMs keeps pace with the \( n = 2 \) harmonic rotation. This gives the direct evidence that the RMP can couple to the 3D structure of ELM instability.

4 SUMMARY

In summary, mixed toroidal harmonic RMPs have been demonstrated to suppress ELMs and control divertor heat load simultaneously on both EAST and DIII-D. Full ELM suppression is observed by using RMPs with mixed static \( n = 3 \) and rotating \( n = 2 \) harmonics in a standard operational window with type-I ELMy H mode plasmas.

Mixed \( n = 2 \) and 3 toroidal harmonic RMP lower the threshold current for ELM suppression compared to the single \( n = 3 \) RMP in DIII-D. Plasma response during ELM suppression using mixed toroidal harmonic RMPs shows that
$n = 2$ field helps to penetrate the $n = 3$ mode which eventually leads to ELM suppression. Linear MHD simulation with the MARS-F code shows good agreement during ELM mitigation in both mode structure and phase, while it has a phase shift to the observed response during ELM suppression in DIII-D, which is similar to that in EAST. These results reveal the common feature of nonlinear bifurcation in plasma response to access ELM suppression.

Experiments using mixed toroidal harmonic RMPs have validated predictions that divertor heat and particle flux can be dynamically controlled while maintaining ELM suppression in both DIII-D and EAST. ELM suppression over one full (and 60%) cycle of a rotating $n=2$ RMP superimposed on a static $n=3$ RMP field has been achieved in DIII-D (and EAST). The 3D pattern of the heat and particle flux to the divertor shifted periodically keeping pace with the phase of the rotating $n=2$ harmonic, which also agrees well with modeling. It is also interesting that the 3D pattern induced by ELMs during ELM mitigation in EAST is locked to the phase of $n = 2$ RMP, which gives the direct evidence that the RMP can couple to the 3D structure of ELM instability.

These results expand physics understanding and potential effectiveness of the technique for reliably controlling ELMs and divertor power/particle loading distributions in future burning plasma devices such as ITER.

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References


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